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This report documents tests conducted at the Naval Coastal Systems Center (NCSC) in support of the Department of Energy's Ocean Thermal Energy Conversion (OTEC) Program. These tests covered the period September 1978 to May 1980 and evaluated flow-driven brushes, recirculating sponge rubber balls, chlorination, and mechanical system/chlorination combinations for in-situ cleanign of two potential heat exchanger materials: titanium and aluminum alloy 5052. Tests were successful when fouling resistance was $<3.0 \times 10^{-4}$ ft^2

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ABSTRACT (continued)

hr-°F/Btu. Results indicated systems and cleaning techniques using brushes, soft sponge balls, and various concentrations of chlorine had some potential for maintaining heat transfer efficiency.

SUMMARY

Systems that have demonstrated the capability to maintain high heat transfer capability for extended periods include:

1. For aluminum:

    a. A 29-mm experimental brush operating on a 4-hour cycle.

    b. A 29-mm "soft" ball operating on a 15-minute cycle in a clean tube subject to chlorination (1 ppm total chlorine residual/ 15 minutes daily).

    c. Low chlorine dosing (1 ppm total chlorine residual/15 minutes daily) followed by periodic "shock" chlorination.

2. For titanium:

    a. A 28-mm brush operating on 4-, 6-, or 8-hour intervals.

    b. Twenty-nine millimetre "soft" balls operating on 15-, 30-, and 60-minute cycles.

    c. Twenty-nine millimetre "soft" balls operating on a 120-minute cycle with pipe subject to 0.5 ppm residual chlorine concentration for 15 minutes daily.

    d. Five tenths parts per million or higher total chlorine residual for 15 minutes daily.

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INTRODUCTION

In response to a request for support from the Department of Energy's (DOE) Technical Agent, Argonne National Laboratory, the Naval Coastal Systems Center (NCSC) has conducted field tests in support of Ocean Thermal Energy Conversion (OTEC). Between September 1978 and May 1980, field tests evaluated the performance of three in-situ cleaning techniques in two potential heat exchanger materials. The cleaning techniques consisted of flow-driven brushes, recirculating sponge rubber balls, and chlorination along with combinations of each mechanical system with chlorination. Each system was tested in both aluminum (Alloy 5052) and titanium pipe. Tests sought to maintain the fouling resistance (Rf) at $<3 \times 10^{-4}$ ft^2-hr-°F/BTU, a stringent cleaning requirement.

BACKGROUND

With an energy crisis facing America, the search for alternative energy sources has taken on national importance. The oceans have long offered the promise of renewable, clean energy and many techniques to extract energy from the oceans have been proposed. Most prominent among these are (1) thermal gradients, (2) geostrophic currents, (3) ocean currents, and (4) wave/tide energy.[1]

Ocean Thermal Energy Conversion (OTEC) is an ambitious program to tap the vast potential of the oceans' thermal resources. The OTEC concept seeks to utilize the thermal difference between warm surface waters and cold deep waters. For OTEC, this thermal difference should exceed a thermal span of 30°F; hence, potential OTEC sites are found between 35 degrees North and South latitudes.[2] [3] Since the thermal efficiency of proposed OTEC plants is low (<3 percent) compared to coal-fired plants (~30 percent), the ocean

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[1]Sea Technology, August 1980, "OTEC Leads The Way In Ocean Energy," pp. 13-18.

[2]Griffin, O. M., 1977, "Power From the Oceans' Thermal Gradients," Sea Technology, August, pp. 35-42.

[3]Hartline, B. K., 1980, "Tapping Sun Warmed Ocean Water For Power," Science 209: 794-796.

thermal power plant must transfer about 10 times as much heat for the same power output. This necessitates an extremely large heat exchanger surface area of great heat transfer efficiency.

The inherent promise of OTEC is that its fuel, warm seawater, is free and virtually unlimited in quantity.[3] A closed-cycle system proposed by OTEC features the Rankine power cycle operating on a span of 20°F temperature differential.[4] System components consist of turbine, pumps, condenser, and evaporator. This system requires a working fluid with (1) good heat transfer characteristics and (2) a high vapor pressure at seawater temperatures. Ammonia is a leading candidate for the working fluid. The working fluid is vaporized in the evaporator, thus generating power by expansion through the turbine. The vapor, at low pressure, is condensed in the heat exchanger and routed back to the evaporator for reuse.

Advantages of such a system are that power turbines can be smaller due to (1) low design pressures and (2) low working fluid densities as well as elimination of the requirement to remove dissolved gasses as is the case in open-cycle systems. These advantages are partially offset by (1) thermal losses in using a secondary working fluid, (2) requirement for extensive heat exchanger surface area of high heat transfer efficiency, and (3) problems associated with the working fluid such as corrosion, handling, and safety.

Due to low thermal efficiencies, extensive heat exchanger surface areas, and parasitic power losses (i.e., power required to operate the plant), the success of OTEC will depend on maintaining a high heat transfer coefficient. The waterside surfaces of any heat exchanger exposed to natural seawater will accumulate a film of slime comprised of living and dead microbial cells, cellular debris, organic molecules and secretions, and inorganic precipitates. This layer, coupled with formation of a corrosion layer, serves as a resistance to heat transfer due to the lower thermal conductivity of such layers. The fouling factor (Rf) is thus a measure of the thermal resistance of a fouling layer and is the reciprocal of the heat transfer coefficient (h) measured in the presence of the fouling film.

The inevitability of fouling has resulted in an initial requirement that Rf be maintained at or below 5×10^{-4} ft^2-hr-°F/Btu.[5] [6] This standard has

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[3]ibid.

[4]Springer, P. C. and Owens, W. L., 1980, "A Measurement Technique for Condenser Tube Biofouling," In Condenser Biofouling Control, Eds: Gary, J. F., Jordon, R. M., Airken, A. H., Burton, D. T., Gray, R. H., Ann Arbor Science, Ann Arbor, MI, pp. 3-42.

[5]Sleicher, C. A. and Rouse, M. W., 1975, "A Convenient Correlation for Heat Transfer to Constant and Variable Property Fluids in Turbulent Pipe flow," Int. J. Heat Mass Transfer 18: 677-683.

[6]Bell, K., "The Effect of Fouling on OTEC Heat Exchanger Design, Construction and Operation," in Proc. OTEC Biofouling and Corrosion Symposium, R. H. Gray, Ed. Seattle, Washington, pp. 19-29 (1978).

been subsequently modified to restrict Rf to less than 3 X 10^{-4} ft^2-hr-°F/Btu.[7] In addition, Bell has proposed an even more stringent requirement of 1 X 10^{-4} ft^2-hr-°F/Btu.[6] Note that a biofilm 0.002 inch (50 μM) thick represents an Rf of 5 X 10^{-4} ft^2-hr-°F/Btu and a 15 to 20 percent reduction in heat exchanger efficiency. It is evident that such stringent cleaning requirements mandate provisions to inhibit formation of the slime layer or to remove any fouling that does form.

FOULING PROCESS

Fouling is generally defined as the formation of inorganic or organic deposits on surfaces. Fouling involves complex hydrodynamic and microbial processes as well as surface electrochemical reactions. Four types of fouling are generally recognized:

1. Formation of inorganic salts by precipitation
2. Corrosion
3. Attachment of particulates to surfaces
4. Biological fouling (biofouling)[8]

This report primarily concerns biofouling since the major OTEC interest is to maintain a high heat transfer coefficient in heat exchangers by inhibiting or removing biological films (biofilms). According to Corpe,[8] biofouling, as a process, consists of four phases:

1. Chemical conditioning or molecular fouling

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[6]ibid.

[7]Cohen, R., 1978, "An Overview of the U. S. OTEC Development Program," Proceedings of the ASME Energy Technology Conference, Houston, TX, 1978 November 6-9.

[8]Corpe, W. A., and Winters, H., 1980, "The Biology of Microfouling of Solid Surfaces with Special Reference to Power Plant Heat Exchangers," In Condenser Biofouling Control, Eds: Gary, J. F., Jordon, R. M., Airken, A. H., Burton, D. T., Gray, R. H., Ann Arbor Science, Ann Arbor, MI, pp. 3-42.

2. Attachment or colonization by microorganisms (Microfouling)

   a. Pioneer bacteria

   b. Other bacteria

3. Colonization by other microorganisms (Macrofouling)

4. Accumulative (Both micro- and macrofouling)

Microfouling, the primary mechanism for degradation of heat exchanger performance, consists of five components:[9]

1. Organic absorption

2. Transport of particles

3. Attachment

4. Growth

5. Re-entrainment

The first stage of microfouling involves the virtually instantaneous sorption of molecules from the flowing water onto the metallic surface, thus "preconditioning" this surface for bacterial adhesion.[8 9 10 11 12 13 14]

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[8]ibid

[9]Characklis, W. G., Bryers, J. D., Trulear, M. G., and Zelver, N., 1980, "Biofouling Film Development and Its Effect on Energy Losses: A Laboratory Study," In Condenser Biofouling Control, Eds: Gary, J. F., Jordon, R. M., Aitken, A. H., Burton, D. T., Gray, R. H., Ann Arbor Science, Ann Arbor, MI, pp. 49-76.

[10]Marshall, K., "Solid-Liquid and Solid-Gas Interfaces," In Interfaces in Microbial Ecology (Cambridge, MA: Harvard University Press, 1976) pp. 27-49.

[11]Fletcher, M., and Loeb, G. I., "The Influence of Substratum Surface Properties on the Attachment of a Marine Bacterium," in Colloid and Interface Surface, Vol. 3, M. Kerker, Ed. (New York: Academic Press Inc., 1976), pp. 459-469.

[12]Baier, R. E., "Influence of the Initial Surface Condition of Materials on Bioadhesion," in Proc. 3rd Int. Congress Marine Corrosion and Fouling, R. F. Acker et al., Eds. (Evanston, IL: Northwestern University Press, 1973), p. 633.

[13]Loeb, G., and Neihof, R., "Marine Conditioning Films," Adv. Chem. Ser. (145):319 (1975).

[14]Baier, R. E. "Surfaces Properties Influencing Biological Adhesion in Biological Systems," in Adhesion in Biological Systems, R. S. Manley, Ed. (New York: Academic Press, Inc., 1970).

Turbulent flow past the metallic surface provides nutrients, organic molecules, and a supply of seed organisms as well as entrained particles that can be incorporated into the slime matrix. Organic molecules modify the surface to make it more wettable and electronegative, thus increasing surface capability to further concentrate organic molecules from flowing water.[8] Molecular fouling does not exceed 0.1 μM and has no effect on fluid flow or heat transfer.[15]

Following surface preconditioning with organic nutrients, initial bacterial colonizers are transported by flow into contact with the metallic surface. Although Brownian movement and cell mobility are important to attachment in stagnant or low flow velocity situations,[16] OTEC's high flow range (~6 feet/second) eliminates these processes as major transport mechanisms. Rather, transport is due to molecular diffusion,[9] eddy transport[9] and, to a lesser extent, chemotaxis.[16 17 18 19]

Initial attachment is reversible when microorganisms "settle" but exhibit Brownian movement and may spontaneously move away from the metallic surface.[20] However, periphytic colonizers quickly develop that adhere firmly and irreversibly. Adherence is mediated through production of polymeric

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[8]ibid.

[9]ibid.

[15]Characklis, W. G., 1980. "Fouling Biofilm Development: A Process Analysis," submitted to Biotechnology and Bioengineering.

[16]Daniels, S. L., 1980, "Mechanisms Involved in Sorption of Microorganisms to Solid Surfaces," in Absorption of Microorganisms to Surfaces, John Wiley & Sons, New York, NY, pp 7-58.

[17]Adler, J., "Chemoreceptors in Bacteria," Science 166:1588-1597 (1969).

[18]Chet, I., and Mitchell, R., "Ecological Aspects of Microbial Chemotactic Behavior," Ann. Rev. Microbiol, 30:221-239 (1976).

[19]Young, L. Y., and Mitchell, R., "The Role of Chemotactic Responses in Primary Film Formation," in Proc. 3rd Int. Congress on Marine Corrosion and Fouling, R. F. Acker et al, Eds. (Evanston, IL: Northwestern University Press, 1973), pp 617-624.

[20]Fletcher, M., 1978, "The Attachment of Bacteria to Surfaces in Aquatic Environments," In Adhesion of Microorganisms to Surfaces, Academic Press, New York, NY, pp. 87-108.

fibrils[20 21 22 23 24] which may form at the cell's poles, thus orienting the cell at right angles to the metallic surface and presenting maximum surface area to flow.[20 21] Firm adhesion is an energy-requiring process that is dependent on protein synthesis.[21]

During growth, the initial colonizers are small, motile, gram-negative rods[23 24 25] which have a selective advantage in irreversible sorption[26] and are capable of irreversible attachment and reproduction at low nutrient level.[27] Since bacteria absorbed to a surface are metabolically more active than those in suspension,[28] probably due to nutrient concentration from

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[20]ibid.

[21]Marshall, K. C., "Mechanisms of Adhesion of Marine Bacteria to Surfaces," in Proc. 3rd Int. Congress Marine Corrosion and Fouling, R. F. Acker et al, Eds. (Evanston, IL: Northwestern University Press, 1973), p. 625.

[22]Costerton, J. W., Geesy, G. G., and Ching, K. J., "How Bacteria Stick," Scientific Am., 238: 86-95 (1978).

[23]Corpe, W. A., 1974, "Periphytic Marine Bacteria and the Formation of Microbial Films on Solid Surfaces," in Effect of the Ocean Environment on Microbial Activities, Eds: R. Colwell and R. Y. Morita, Univ. Park Press, p 397-417.

[24]Gerchakov, S. M., Marszalek, D. S., Roth, F., and Udey, L., "Succession of Periphytic Microorganisms on Metal and Glass Surfaces in Natural Seawater," in Proc. 4th Int. Congress Marine Corrosion and Fouling, V. Romanovsky, Ed., Antibes, France, P 203 (1976).

[25]Little, B. J. and Lavoie, D. M., 1980, "Gulf of Mexico Ocean Thermal Energy (OTEC) Biofouling Experiment." In Condenser Biofouling Control, Eds: J. F. Gary, R. M. Jorden, A. H. Aitken, D. T. Burton, and R. H. Gray, Ann Arbor Science, Ann Arbor, MI, pp 121-140.

[26]DiSalvo, L. "Contamination of Surfaces by Bacterial Neuston," Limnol, Occeanog. 18: 165-168 (1973).

[27]Friedman, B. A., Duggan, P. R., Pfuster, R. M., and Remsen, C. C., "Structure of Exocellular Polymers and Their Relation to Bacterial Flocculation," J. Bacteriol, 98: 1328-1334 (1969).

[28]Hendricks, S. W., "Sorption of Heterotrophic and Enteric Bacteria to Glass Surfaces in a Continuous Culture of River Water," Appl. Microbiol. 28: 572-578 (1974).

flow,[29 30 31] a proliferation of micro-organisms occurs with consequent increase in capsular material (i.e., extracellular polysaccharide). Micro-organisms are generally contained as discrete units or cell aggregates within the slime matrix of capsular polysaccharides and form less than 10 percent of the biofilm.[15] This capsular material, in turn, attaches any particulate material presented to the film by flow and incorporates the particulates into the biofilm. The adhesion of entrained particles results in (1) increasing film thickness, (2) degradation of the heat transfer coefficient, (3) entrapment of further particles for growth, (4) corrosion, and (5) an increase in frictional resistance. The slime matrix aids the microorganisms by resisting stresses in the environment.

Secondary periphytic bacteria follow the initial colonizers and grow better in the presence of the pioneer bacteria than without them.[20] These may include filamentous, stalked, or budding bacteria which can, under proper conditions, form bacterial mats.[8 23] These microbes gain an ecological advantage as the biofilm develops since they increase the surface area in contact with turbulent flow and provide attachment sites for primary colonizers.[19 32]

In the accumulative phase of biofouling, film characteristics such as thickness, density, and rate of formation will be controlled by nutrient transport, pipe surface temperature, shear forces (flow velocity), light, pipe

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[8]ibid.

[15]ibid.

[20]ibid.

[23]ibid.

[29]Zobell, C. E. "The Effect of Solid Surfaces Upon Bacterial Activity," J. Bacteriol, 46: 39-56 (1943).

[30]ZoBell, C. E. "Substratum as an Environmental Factor for Aquatic Bacteria, Fungi and Blue-Green Algae," in Marine Ecology, Vol. 1, Environmental Factors, O. Kinne, Ed. (New York: John Wiley & Sons, Inc., 1972), pp 1252-1270.

[31]Characklis, W., "Attached Microbial Growths - I. Attachment and Growth," Water Res. 7: 1113-27 (1973).

[32]LaMotta, E. J., "Kinetics of Growth and Substrate Uptake in a Biological Film System," Appl. Environ. Microbiol. 31: 286-293 (1976).

composition, and water quality (e.g., pH, O_2, numbers and kinds of organisms, types of suspended particles). Film thickness is further dependent on the width of the viscous sublayer.[9] The viscous sublayer is a stagnant, transition region between the metal surface and turbulent flow. Its width is a function of flow velocity and tube diameter. Turbulent flow-induced shear stress will not affect slime layers whose thickness is less than that of the viscous sublayer. When the slime layer exceeds the viscous sublayer width, considerable shear forces are extended on the slime layer that may result in re-entrainment.

Surface shear and sloughing are two mechanisms of re-entrainment. Surface shear, described above, acts to remove susceptible portions of the slime layer. As the film accumulates, the second mechanism, sloughing, becomes evident. Sloughing is a massive removal of slime attributed to oxygen and/or nutrient depletion deep within thicker, denser biofilms.[9 32 33] Transport of oxygen and nutrients is by passive diffusion. As layer thickness increases, the maximum distance over which passive transport is effective is exceeded, resulting in anoxia or nutrient depletion.[34] In either case, anaerobes will proliferate, resulting in losses to the film as well as intensifying corrosion due to acid production.[8 9]

When portions of the film are lost or removed by cleaning, the preconditioned surface with available nutrients is suitable for a rapid regrowth. This regrowth is frequently more rapid than that from clean surfaces and is illustrated by Detwiler,[35] who reported that condensers, manually cleaned, experienced at least 15 to 20 percent reduction in heat transfer after only 10 hours following re-exposure to flowing seawater.

Once completed, primary film formation (microfouling) is succeeded by initial macrofouling in the form of holozoic protozoa such as ciliates and amoeba.[8] Flagellates also occur which utilize lytic products of the film.

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[8]ibid.

[9]ibid.

[32]ibid.

[33]Hohen, C. H. and Ray, A. D., "Effects of thickness on Bacterial Film," Journal WPCF 45:11, November 1973.

[34]Kirkpatrick, J. P., McIntyre, L. V., and Characklis, W. G., 1980, "Mass and Heat Transfer in a Circular Tube with Biofouling," Water Research 14: 117-127.

[35]Detwiler, D. S., "Improving Condenser Performance with Continuous In-Service Cleaning of Tubes," American Societv for Testing Materials Publication STP 538.

The so-called primary foulers--barnacles, bryozoans, and hydroids--quickly follow. Finally, secondary foulers such as anemones, ascidians, and mussels occur. Macrofouling results in restricted flow due to biomass accumulation as well as sediment entrapment.

At least 72 percent of the total resistance to heat transfer in condenser tubes is attributed to waterside resistances. The waterside resistances, in turn, are composed of resistances derived from the viscous or stagnant sub-layer located between turbulent flow and the pipe wall (39 percent) and biofouling (33 percent). Heat transfer is accomplished by two mechanisms, each of which is influenced by biofilm development. Conductive heat transfer through condenser walls is one heat transfer mechanism severely affected by biofilm thickness. Since the biofilm is 98 to 99 percent water,[15] the slime matrix has the thermal conductivity of water. It is therefore likely that corrosion products and inert suspended solids presented to the slime by sea-water flow may be incorporated into the slime matrix, reducing the thermal conductivity (conductive heat transfer).[36]

The second mechanism of heat transfer is convective heat transfer. This is heat removed through fluid mixing or motion. Biofilm development above a critical thickness increases frictional resistance between the pipe and seawater flow, resulting in a pressure drop and an increase in electrical consumption.

In summary, microfouling results in a slime layer which degrades condenser performance. For OTEC to succeed, an in-situ biofouling countermeasure (cleaning technique) must be used to prevent or remove the slime layer.

BIOFOULING COUNTERMEASURES

With the problem of slime accumulations in mind, a biofouling countermeasures program was established at the Naval Coastal Systems Center (NCSC), Panama City, Florida. Many techniques have been proposed as countermeasures systems such as (1) flow-driven brushes ,[37 38 39] (2) recirculating sponge

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[15]ibid.

[36]Characklis, W. G., 1979, "Biofilm Development and Destruction In Turbulent Flow," Ozone: Science and Engineering 1: 167-181.

[37]Rice, M. S., Hagel, D., Conn, A. F., 1977, "Methods for Cleaning OTEC Heat Exchangers," Report #7701-1, Hydronautics, Inc., Columbia, MD.

[38]Fritsch, A., Adamson, W., and Castelli, V., "An Evaluation of Mechanical Cleaning Methods for Removal of Soft Fouling from Heat Exchanger Tubes in OTEC Power Plants," Proc 5th OTEC Conference, Seattle, WA, October 10-12, 1977, pp 159-166.

[39]Conn, A. F., Rice, M. S., and Hagel, D., "Ultra Clean Heat Exchangers - A Critical OTEC Requirement," Proc. 4th OTEC Conference, New Orleans, LA, March 22-24, 1977, pp. VII-11 to VII-14.

rubber balls,[37 38 39] (3) chlorination,[37 38 39] (4) water jets,[37 38 39] (5) abrasive slurries,[40 41] (6) ultrasonics,[39 42] and (7) copper toxicity.[43] Of these, three systems were recommended for immediate application to in-situ cleaning of heat exchangers with "off-the-shelf" components. These were flow-driven brushes, recirculating sponge rubber balls, and chlorination, as well as combinations of each mechanical system with chlorination. Each system was tested in both aluminum (Alloy 5052) and titanium pipe. A test was assumed to be successful when fouling-induced thermal resistance (Rf) remained at or near the target level of 1×10^{-4} ft^2-hr-°F/Btu (Rf = 0.0001 or Rf = 1.0). Except for limited biological tests in which the maximum Rf was 5.0, cleaning tests were terminated when Rf exceeded 3.0.

FLOW-DRIVEN BRUSHES

This cleaning system has been described elsewhere.[44] Basically, however, the system involves the use of brushes slightly larger in diameter than that of the pipe. Each pipe is equipped with a cage at each end of the tube. The brush normally resides in the downstream cage. Periodically the flow is reversed, driving the brush to the opposite end of the pipe where it is again captured in the opposite cage. The brush remains trapped briefly in the cage and then, upon return of normal flow, returns to the starting position; i.e., downstream cage. Cleaning results from shear forces generated by brush movement. These forces should be sufficient to prevent or remove biofilm accumulations.

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[37]ibid.

[38]ibid.

[39]ibid.

[40]Kineiski, E. H., 1978, "Review of OTEC Test Facilities," Proceedings of the Fifth OTEC Conference, Seattle, Washington, October 10-12, 1977, pp 1-6.

[41]Mann, M. J., 1979, "Possible Cu-Ni-Clad Steel Material and Abrasive Slurry Cleaning System for Plate-Fin-Type OTEC Heat Exchangers," in Proceedings of the Sixth OTEC Conference, Washington, DC, June 19-22.

[42]Pandolfini, P. P., Avery, W. H., and Hill, F. K., "Experiments on Ultrasonic Cleaning of a Shell-less Folded Aluminum Tube, OTEC Heat Exchanger," Proceedings of the Sixth OTEC Conference, Washington, DC, June 19-22, 1978, pp 12.8-1 to 12.8-6.

[43]Smith, C. W., Kirk, B. J., and Blume, W. J., "Possible Use of the Cathelco System to Control Fouling in OTEC Systems," Proceeding of the Sixth OTEC Conference, Washington, DC, June 19-22, 1979, pp 12.11-1 to 12.11-3.

[44]Nubel, E. D., "Automatic Tube Cleaning System - Brush and Cage Principle," In Proceedings of the Fourth OTEC Conference, March 22-24, 1977, pp VII-61 to VII-63.

Advantages of using this system include:

1. Each pipe has its own brush
2. Off-the-shelf components
3. In-situ cleaning
4. Estimated brush life of 5 years
5. Automated, requiring little monitoring
6. Can be used with finned tubes
7. Flow reversal frees foreign objects
8. Disrupts the stagnant laminar water film within the pipe, increasing heat transfer and reducing rate of fouling
9. Compatible with chemical cleaning[37 38 39 42 44 45]

Problems of such a system include:

1. Complex systems required for flow reversal
2. Abrasion of pipes
3. Cleaning system (cage/brushes) becomes fouled
4. Questions of brush wear in contrast to the expected brush life
5. Prone to clogging due to fouling accumulations and debris from water flow
6. Basically an intermittent cleaning system

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[37]ibid.

[38]ibid.

[39]ibid.

[42]ibid.

[44]ibid.

[45]Burton, D. T., "Biofouling Control Procedures for Power Plant Cooling Water Systems," In Condenser Biofouling Control, Eds: Gary, J. F., Jordon, R. M., Aitken, A. H., Burton, D. T., Gray, R. H., Ann Arbor Science, Ann Arbor, MI, pp 49-76.

7. Debris screening may be required

8. Removal of protective oxide film within the pipe

9. Head losses due to flow restriction through cages, etc.[37 38 39 42 44 45]

RECIRCULATING SPONGE RUBBER BALLS

Recirculating sponge rubber balls (SRBs) are designed to provide continuous mechanical cleaning during normal condenser operation. In a large scale system, slightly oversize balls are injected into fluid flow where distribution into individual pipes occur. Ball distribution is thus dependent (1) upon the specific gravity of cooling fluid and SRBs and (2) on the number of balls used. Each tube should receive a ball on the average of every 5 minutes. Ball movement is controlled by (1) flow velocity and (2) a pressure differential between fluid inlet and outlet. During movement, the oversize ball is compressed thus providing an extended cleaning area. Cleaning results from a continuous "wiping" of the pipe's interior. As balls exit the pipes, they are screened out of flow and pumped back to the injectors for reuse.

SRBs are described by their diameter and density. Thus, a 28-mm diameter ball may be "soft," "normal," or "hard" in density and may also have an abrasive coating. Density designations are arbitrary classifications made by the supplying company (Amertap Corporation).

Advantages of this system include:

1. Essentially continuous cleaning

2. In-situ cleaning

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[37]ibid.

[38]ibid.

[39]ibid.

[42]ibid.

[44]ibid.

[45]ibid.

3. Off-the-shelf components
4. No requirement for reversed flow
5. Great variety in ball resiliency and abrasiveness
6. Disrupts laminar film
7. Automatic ball collection for injection
8. Compatible with chemical cleaning [37] [38] [39] [46]

Disadvantages include:

1. Random ball distribution
2. Weekly maintenance required
3. Short ball life
4. Slight head loss due to screening
5. Debris screening required
6. Power penalty for ball injection and capture
7. Not suitable for finned tubes
8. Removal of protective oxide films[37] [38] [39] [46]

CHLORINATION

Historically, chlorine has been the technique of choice for disinfection and biofilm control in waste water/power plant applications. Chlorine acts in two ways: (1) actual disinfection or killing of microbes and (2) oxidation of biofilm capsular components, weakening the film for removal by shear forces.

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[37]ibid.

[38]ibid.

[39]ibid.

[46]Kern, W. I., "Increasing Heat Exchanger Efficiency Through Continuous Mechanical Tube Maintenance," In Proceedings of Fourth OTEC Conference, March 22-24, 1977, pp VII-64 to VII-78.

The effectiveness of chlorine is well documented.[37 38 39 47 48] Therefore, chlorine use is not so much a question of effectiveness as of minimization since excessive oxidants can have serious environmental effects in receiving waters.

The chlorine system consists of electrolytic cells positioned upstream operating either intermittantly or continuously. Sufficient chlorine is generated to satisfy the chlorine demand of fluid flow and to provide a mean daily average residual chlorine concentration of <0.25 ppm. Residual concentration is automatically monitored at the condenser exit by the system controller which, in turn, controls chlorine generation.

Advantages of chlorination include:

1. On-site generation without storage requirements
2. Documented effectiveness
3. Automated, simple system
4. Limited maintenance
5. Availability of off-the-shelf components
6. In-situ cleaning
7. Compatibility with mechanical systems [37 38 39 47 48]
8. Suitable for finned systems

Disadvantages include:

1. Parasitic power losses
2. Incompatible with brass and many aluminum alloys
3. Environmental effects/restrictions

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[37]ibid.

[38]ibid.

[39]ibid.

[47]Norrman, G., Characklis, W. G., and Bryers, J. D., "Control of Microbial Fouling in Circular Tubes with Chlorine," Dev. Ind. Micobiol. 18, 581-590 (1977).

[48]Faua, J. A. and Thomas, D. L., 1978, "Use of Chlorine to Control OTEC Biofouling," Ocean Engineering, Vol. 5: 269-288.

4. Not effective against inorganic fuling and, to a lesser extent, established macrofouling

5. May promote corrosion or scaling

6. Less effective against established biofilms at feasible chlorine concentrations[37 38 39 47 48]

TEST SITE CHARACTERIZATION

The Panama City OTEC site is located on St. Andrew Bay (Figure 1), an estuary approximately 100 miles east of Pensacola, Florida. The estuary consists of meandering, deep water channels surrounded by extensive Thalassia beds. The central portion of the bay, upon which the test site is located, varies from 35 to 50 feet in depth. This depth, coupled with a limited fresh water feed source, makes the St. Andrew Bay system unique among Gulf Coast estuaries.[49] The bay is classified as a positive estuary, although fresh water input barely exceeds evaporation.[50] This limited fresh water input contributes to the high salinities (24 to 30 percent range) recorded at the test site. Water quality conditions within the bay and coastal waters have been described elsewhere.[51 52 53 54] However, during the course of this

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[37]ibid.

[38]ibid.

[39]ibid.

[47]ibid.

[48]ibid.

[49]Bense, J. A., "A Swift Creek-Weeden Island Village Complex in the St. Andrew Bay System of the Northwest Florida Gulf Coast," 34th Annual Southeastern Archaelogical Conference, Lafayette, LA, 1977.

[50]McNulty, J. K., Lindall, W. N., and Sykes, J. E., Cooperative Gulf of Mexico Estuarine Inventory and Study, Florida: Phase I, Area Description, NOAA Technical Report NMFS CIRC-368, Seattle, WA, 1972.

[51]Water Quality Study--St. Andrew Bay, Florida, EPA, Office of Enforcement, National Enforcement Investigations Center, Denver, CO, 1975.

[52]Salsman, G. G. and Ciesluk, A. J., "Environmental Conditions in Coastal Waters Near Panama City, Florida," NCSC Technical Report 337-78, 1978.

[53]Loftin, H. G. and Lott, D. F., 1980, "A Summary of Results of the NCSC Data Base Survey of Water Quality: January 1975 to October 1979," NCSC Technical Note, May 1980.

[54]Lott, D. F. and Tuovila, S. M., "Fouling Countermeasures - Status of Two Mechanical Cleaning Systems and Chlorination," Proceedings of Sixth OTEC Conference, Washington, DC, June 19-22, 1979.

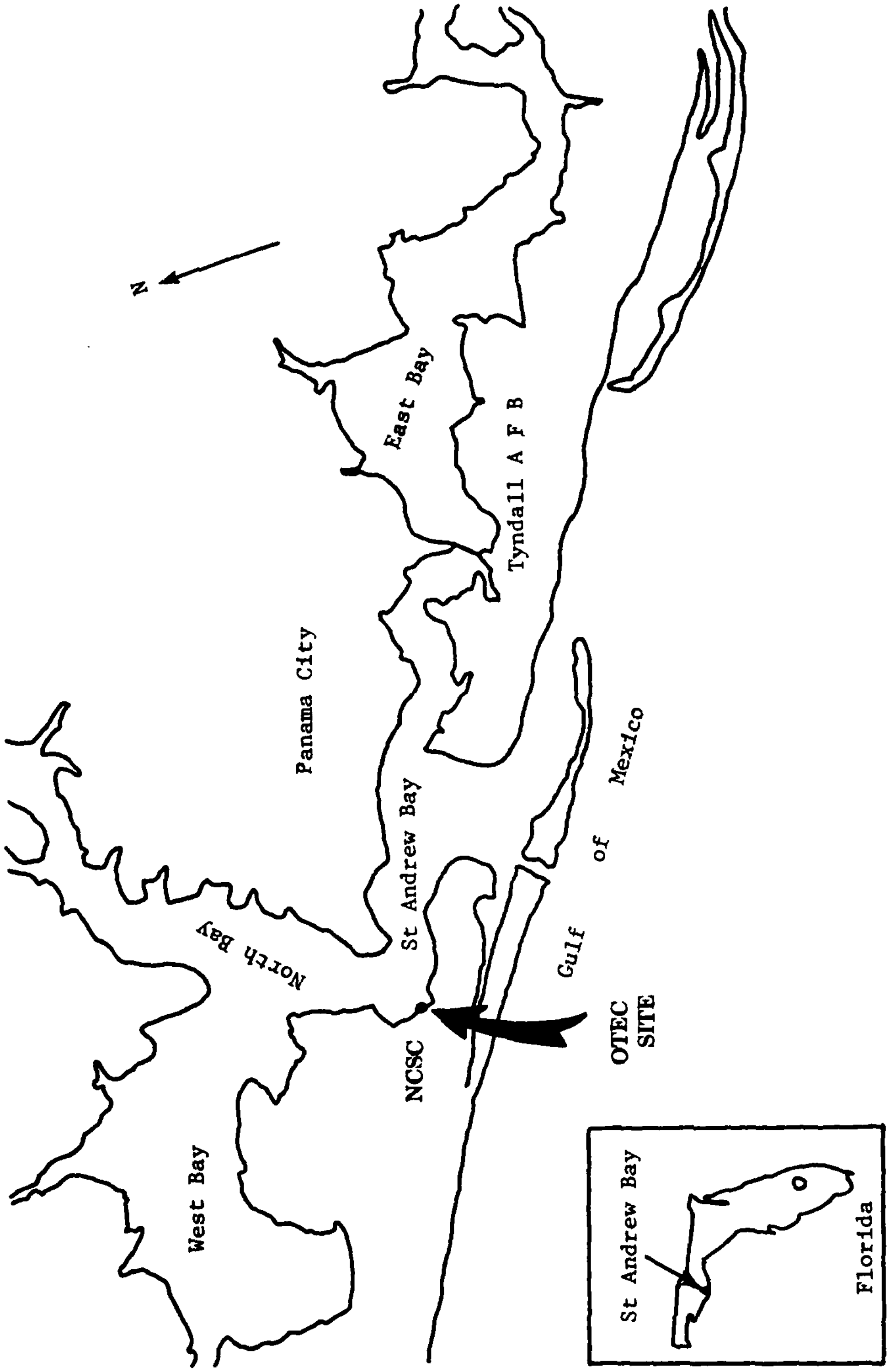

FIGURE 1. LOCATION OF PANAMA CITY OTEC SITE

study, test site characterization was performed for selected water quality parameters. Average values for water quality data are summarized in Table 1 with a detailed graph of each parameter included as Appendix A.

The data in Table 1 describe a relatively nonpolluted environment with an extensive microbial community. Predictably, primary film formation was rapid year-round. The advantages of this estuarine site, although not characteristic of typical OTEC sites where strong vertical thermal gradients prevail, were heavy year-round fouling and avoidance of many problems that plague testing at remote sites. Estuarine testing here is thus a worse case situation and it has been conjectured that continued operation of a moored OTEC platform may sufficiently alter its local environment to resemble such an estuarine situation.[55]

Because of chlorination testing, two further considerations must be addressed during test site characterization: (1) surface currents and (2) chlorine demand of bay waters.

Dye tracer studies were made of surface currents and their effect on locations of the water intake for test systems. This was particularly important in chlorination studies where reuse of chlorinated water is prohibited. Six dye tracer studies were carried out at the NCSC OTEC site (Ammunition Pier-AP). Each study used a surface release of fluorescein dye at various stations surrounding the test site. A composite of surface currents is illustrated in Figure 2. Results indicate that flow down the ship channel dominates wind-induced surface currents. By siting the water intake on the north arm of the pier, reuse of chlorinated water was minimized.

Chlorine demand measurements were also important for chlorination minimization studies and for comparisons with other OTEC test sites. In order to minimize the chlorine produced yet have enough chlorine available for primary film prevention and removal, it was essential that information on variability in chlorine demand be determined. This information would allow eventual automatic control of chlorine generation. Two studies were done. The first addressed variability in chlorine demand over a 24-hour period. Seawater samples were collected at hourly intervals and analyzed ampherometrically for chlorine demand at contact times of 0, 0.5, 1, and 5 minutes. Variability over a 24-hour period was generally less than 1 ppm for all contact times tested (Figure 3). Although chlorine demand increased somewhat with time, little real difference was noted in demand at the various contact times. In addition, differences between chlorine demand at zero minutes and 5 minutes seldom exceeded 1 ppm.

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[55]Loeb, George, Sixth OTEC Conference Biofouling and Corrosion Panel Discussion.

TABLE 1

TEST SITE CHARACTERIZATION USING SELECTED WATER QUALITY PARAMETERS

File No.	Parameter	Units	Mean	Standard Deviation	Number of Samples	Maximum	Minimum
3	Conductivity	mmhos/cm	37.72	6.83	77	54.65	24.22
4	Salinity	ppt	27.30	3.40	80	33.66	19.76
5	Temperature	°C	20.21	6.54	80	30.27	8.09
6	Acidity	pH	8.00	0.24	80	8.40	6.8
7	Tubidity	NTU	1.57	0.49	76	2.90	0.68
8	Dissolved Oxygen	ppm	6.83	1.47	79	10.40	3.7
9	Biological Oxygen Demand	ppm	2.93	8.16	76	72.00	0.08
10	Nitrogen, Ammonia	Mg $N\text{-}NH_3$/L	0.03	0.02	73	0.10	1×10^{-3}
11	Nitrogen, Nitrate	Mg $N\text{-}NO_3$/L	0.02	0.02	78	0.09	1×10^{-3}
12	Phosphate, Phosphorous	Mg $P\text{-}PO_4$/L	0.04	0.02	76	0.11	1×10^{-3}
15	Silica, Silicates	Mg/L	0.40	0.30	62	1.20	0.06
13	Total Organic Carbon	Mg C/L	541.56	1286.54	77	7580.00	2.32
14	Adenosine Triphosphate	Mg ATP/L	8.83×10^{-3}	0.01	61	0.06	3.54×10^{-4}
16	Total Bacteria	Cfu/ML	1343.46	2185.06	35	10,050.00	13.0

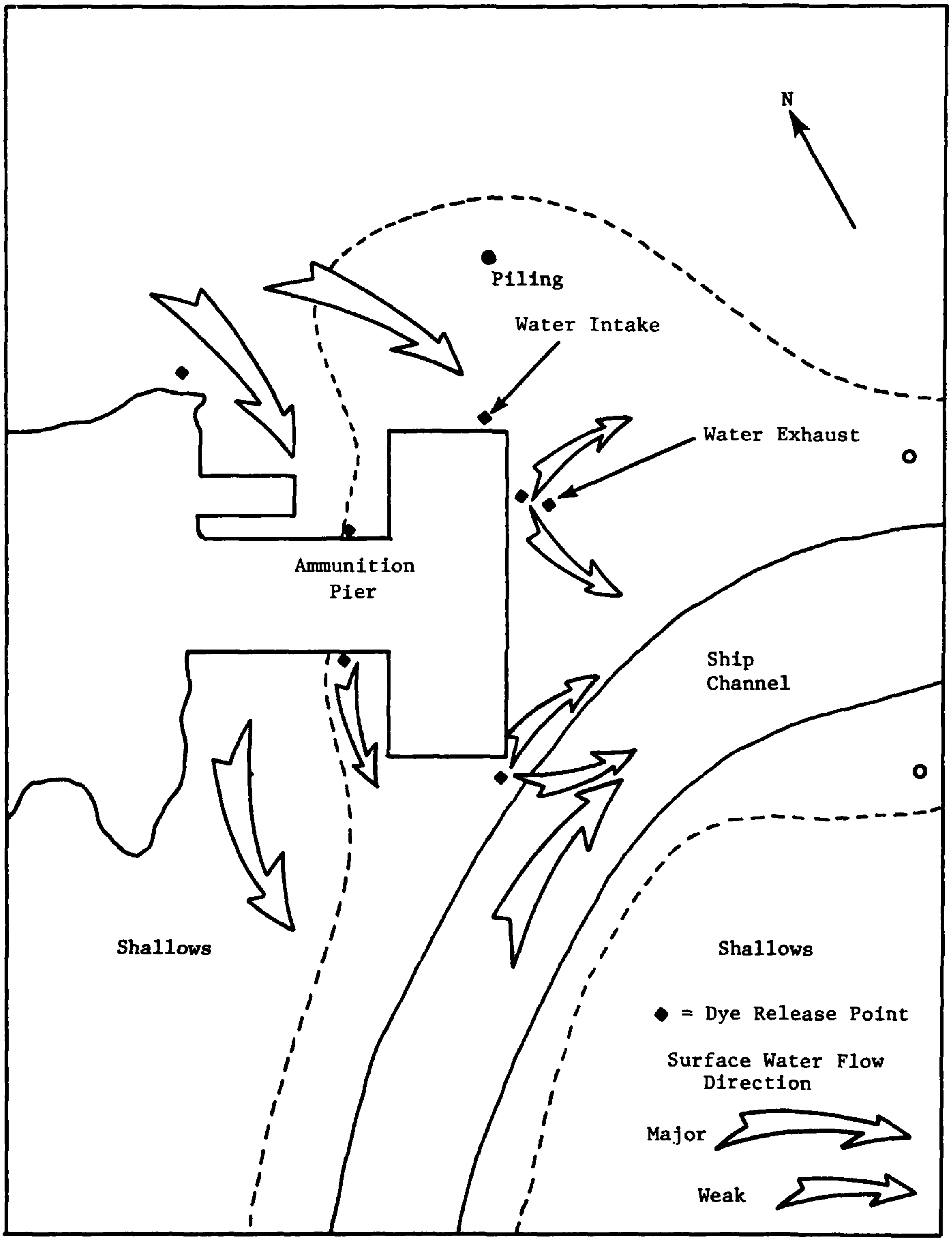

FIGURE 2. SURFACE CURRENTS AT AMMO PIER OTEC TEST SITE

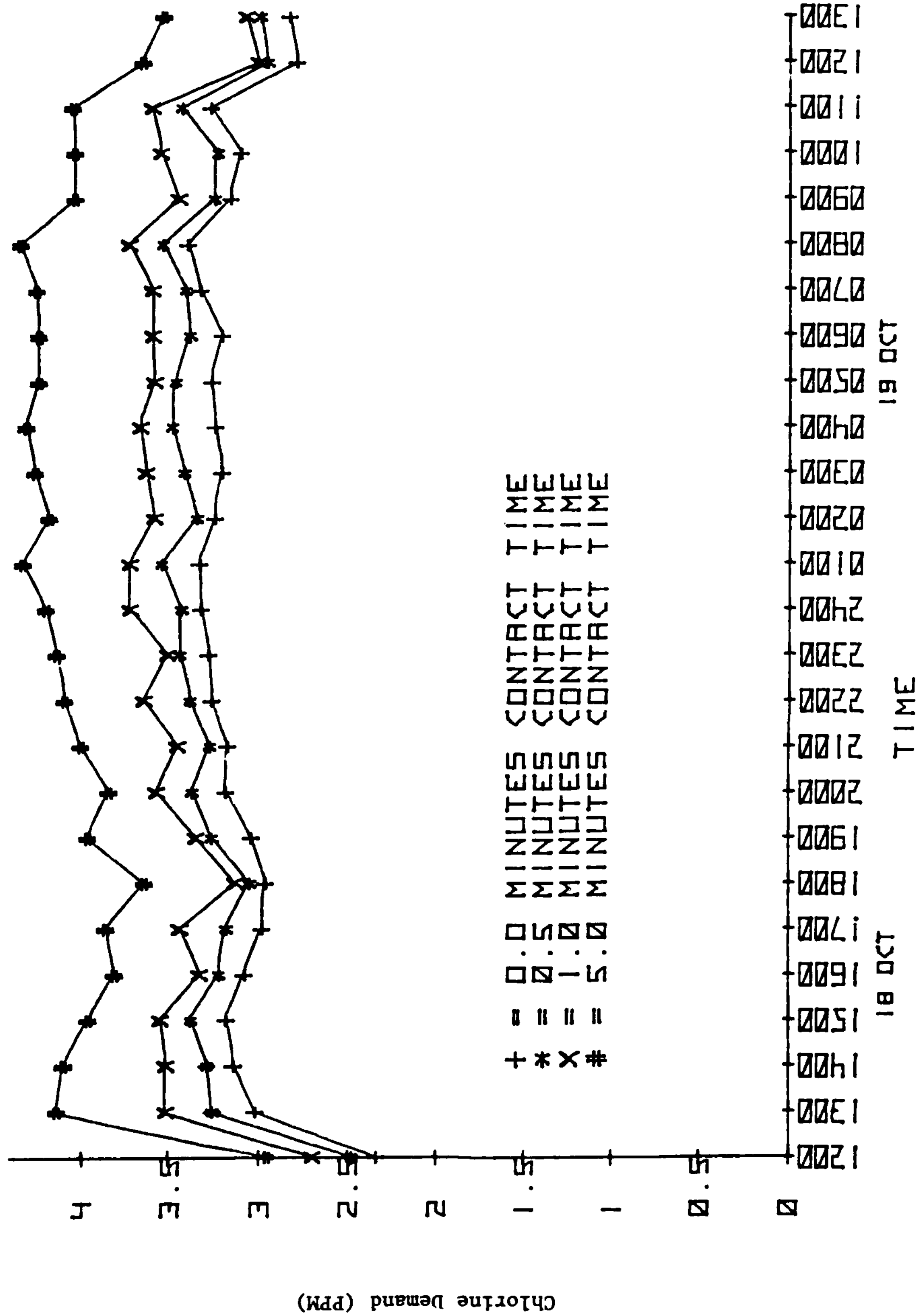

FIGURE 3. VARIATION IN CHLORINE DEMAND OVER 24-HOUR PERIOD

The second study involved variations in chlorine demand at tidal extremes over a 5-day period. During the study period, tidal range was 1.6 feet (0.5 m), a maximum for St. Andrew Bay. The variability in chlorine demand at low (Figure 4) and high (Figure 5) tide was determined for a variety of chlorine contact times. Results indicated that chlorine demand increases with contact time but was less than 1 ppm difference for the contact times tested. Variability in chlorine demand at high and low tides is indicated in Figures 6 through 9 for 0, 0.5, 1, and 5 minutes, respectively. High tide did reduce chlorine demand, but the demand decreased by less than 1 ppm in most cases. This meant chlorine demand varied over a narrow range for St. Andrew Bay and offered hope that automatic control of chlorine generation is feasible.

TEST SYSTEM

TEST FACILITY

The Panama City test facility is shown in Figure 6. The major components include: (1) seawater intake, (2) suction pumps, (3) seawater manifold, (4) control units, (5) chlorination units, (6) recirculating sponge rubber ball units, (7) flow-driven brush units, (8) instrumentation building, (9) instrumentation trailer, and (10) data acquisition system. The system was a single stage pumping system operating at a pressure of 30 psig and supplied with feed water from an intake depth of 7 feet (2.1 m).

This facility was extensively modified from that conceived and built by Fritsch, et al.[38] System components were continually upgraded or modified to eliminate problems encountered during testing. Detailed documentation of electronic and mechanical subsystems may be found in separate papers published elsewhere.[56] [57]

DATA COLLECTION

Data acquisition and reduction was done by the Digital Electronics Corporation PDP 11/34 computer. The software used for data acquisition and

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[38]ibid.

[56]Lott, D. F., "Ocean Thermal Energy Coversion - Electronic Systems," Naval Coastal Systems Center Technical Memorandum 296-80, December 1980.

[57]Lott, D. F., "Ocean Thermal Energy Coversion - Mechanical Systems," Naval Coastal Systems Center Technical Memorandum 297-80, December 1980.

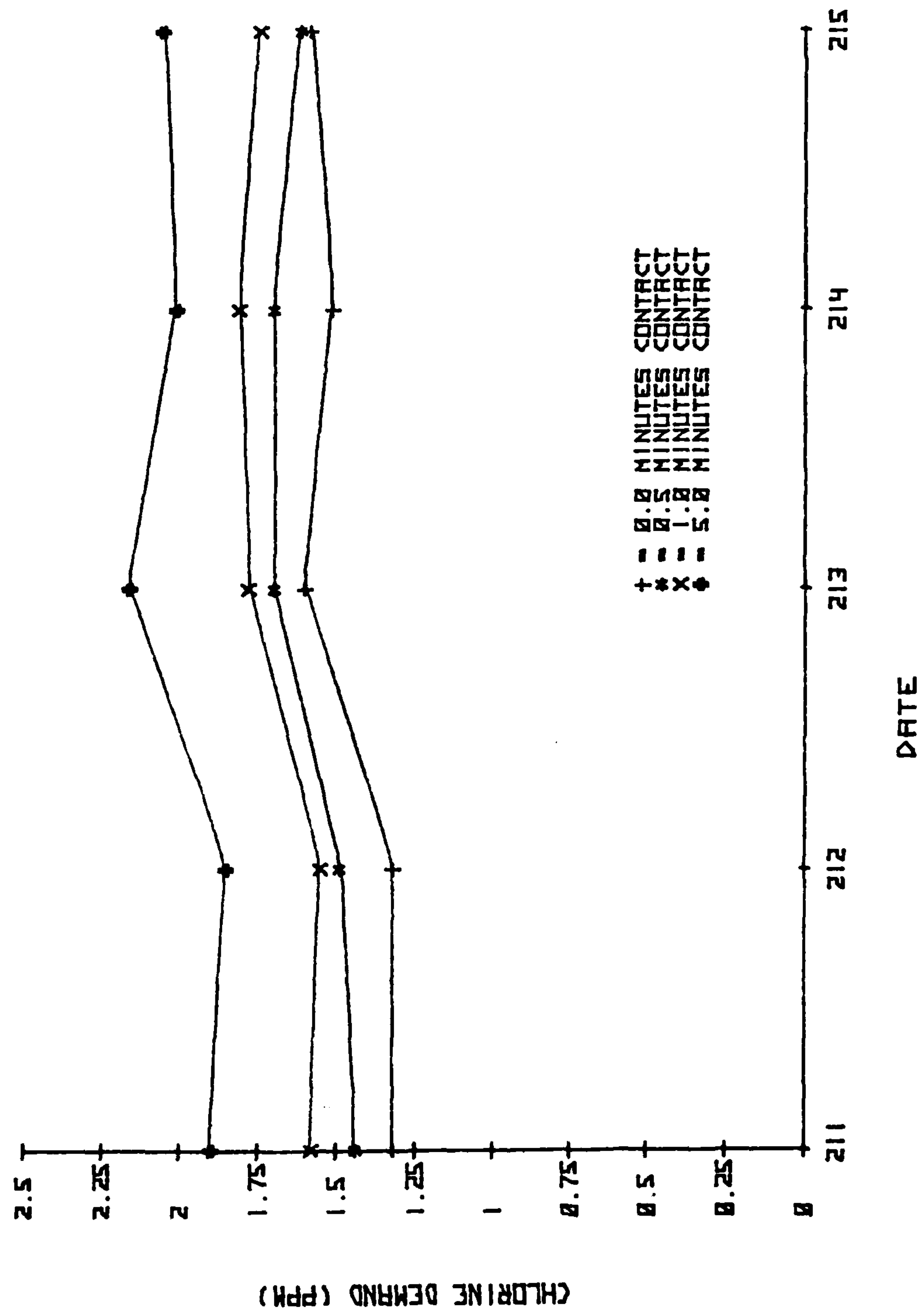

FIGURE 4. VARIATION IN CHLORINE DEMAND AT LOW TIDE - 5-DAY PERIOD

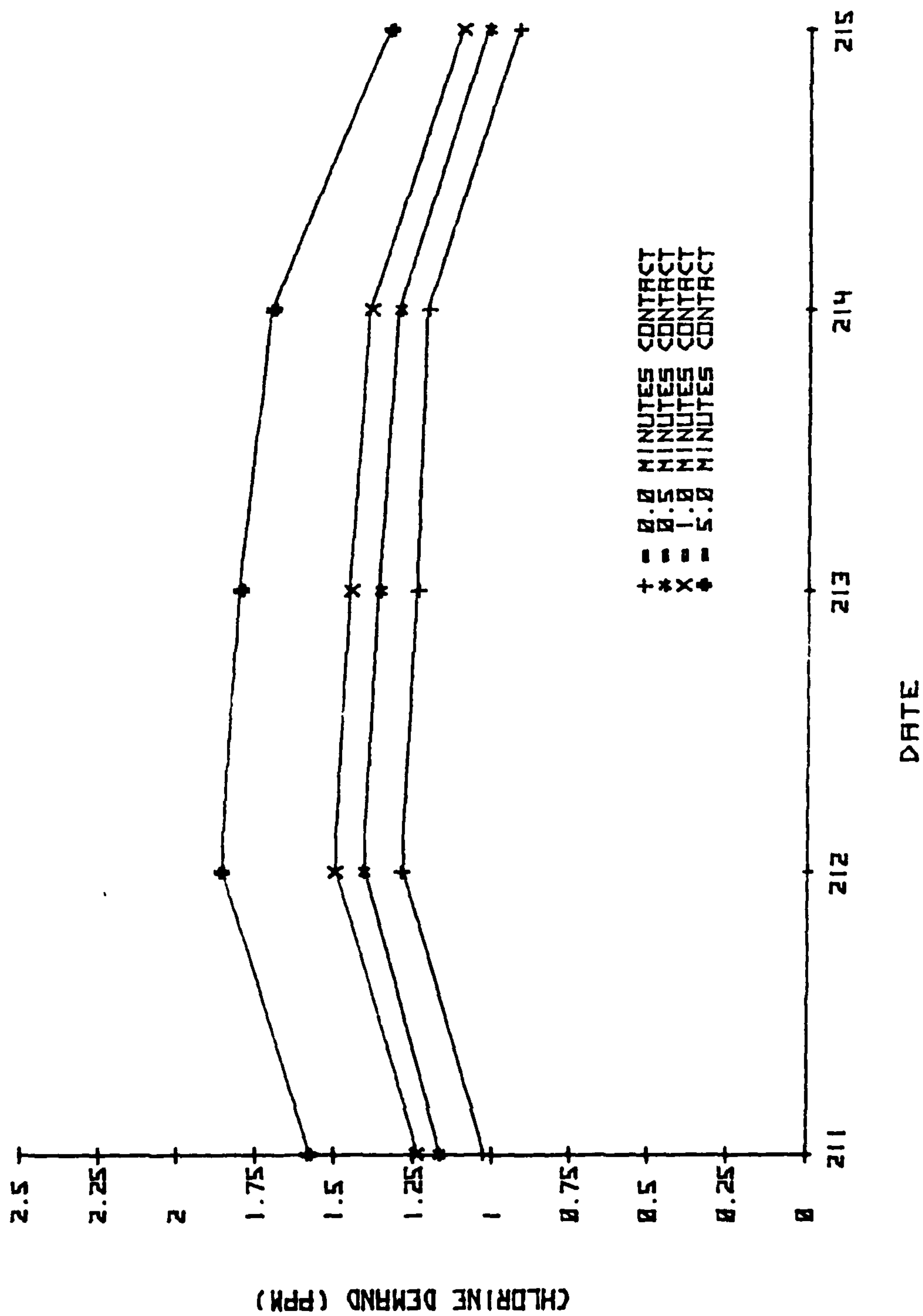

FIGURE 5. VARIATION IN CHLORINE DEMAND AT HIGH TIDE - 5-DAY PERIOD

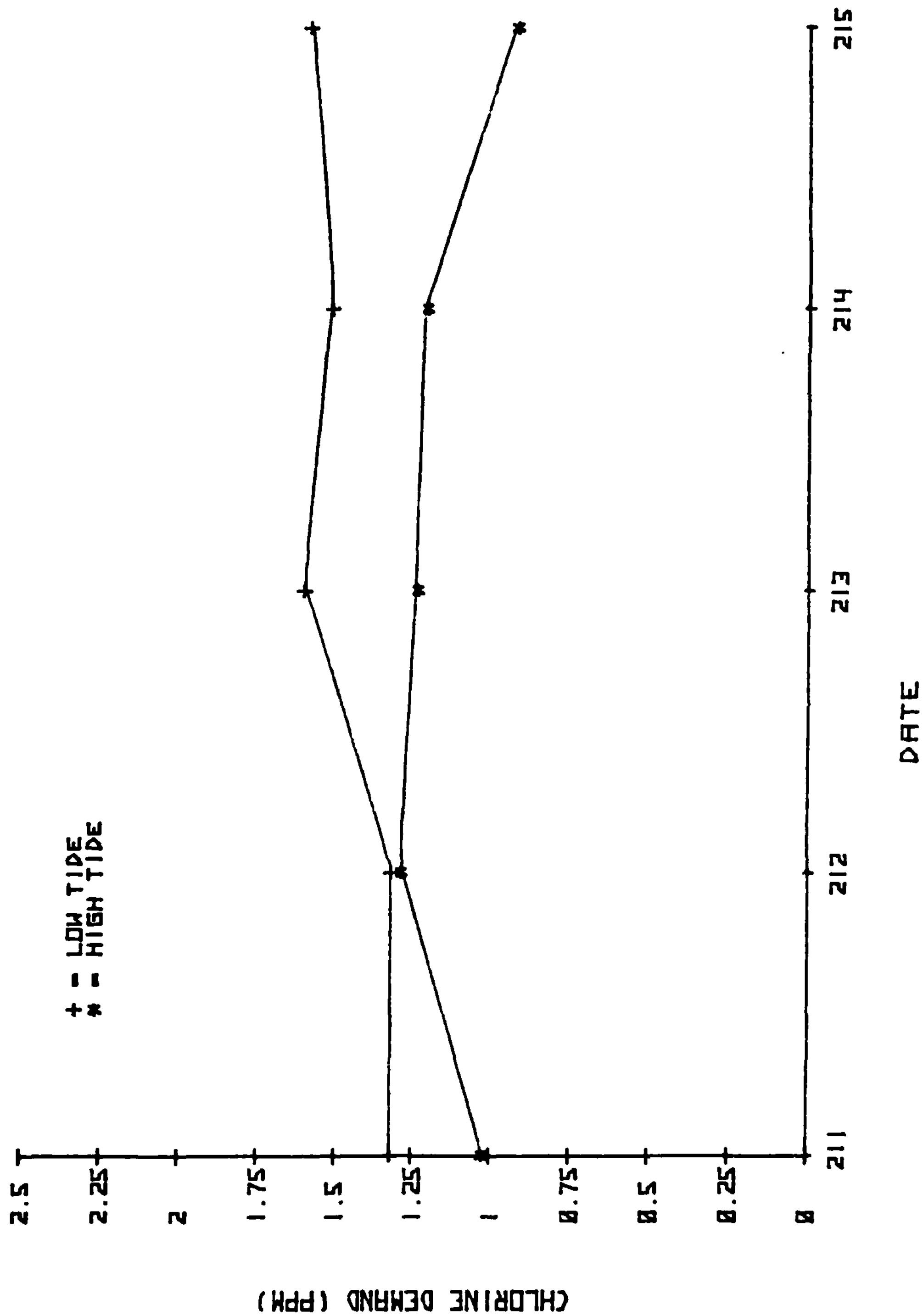

FIGURE 6. VARIATION IN CHLORINE DEMAND AT ZERO MINUTES CONTACT TIME - 5-DAY PERIOD

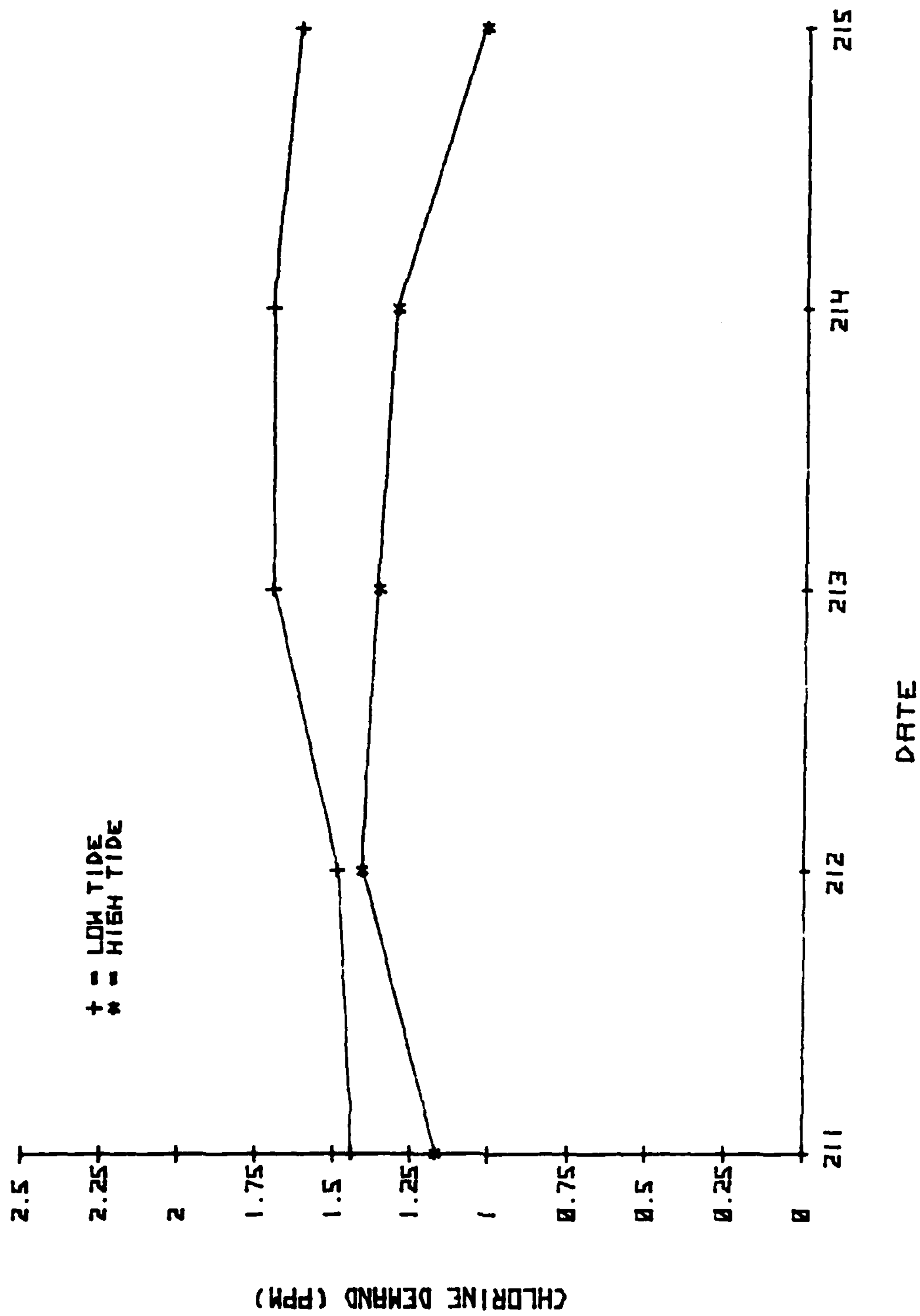

FIGURE 7. VARIATION IN CHLORINE DEMAND AT 0.5 MINUTE CONTACT TIME - 5-DAY PERIOD

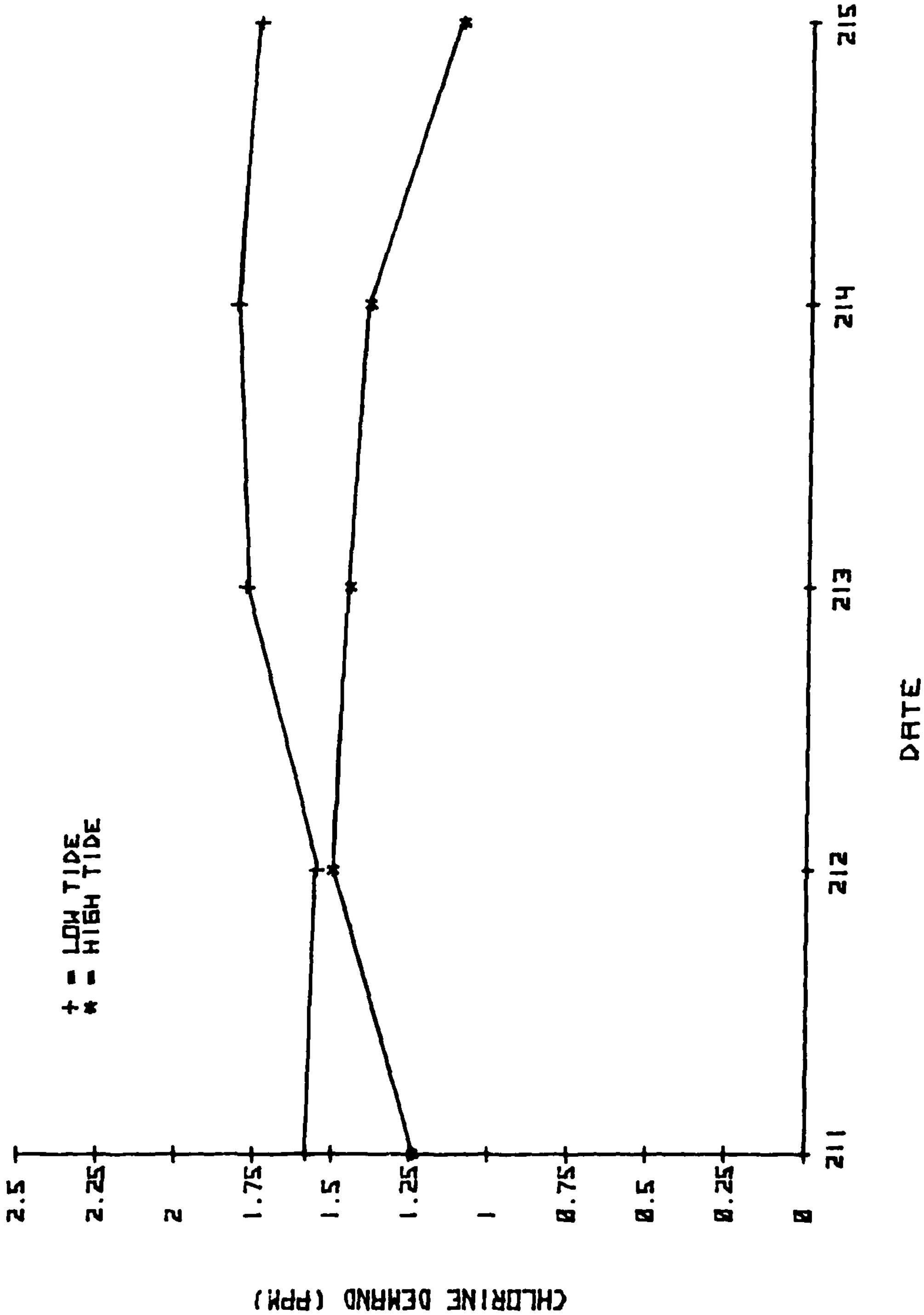

FIGURE 8. VARIATION IN CHLORINE DEMAND AT 1.0 MINUTES CONTACT TIME - 5-DAY PERIOD

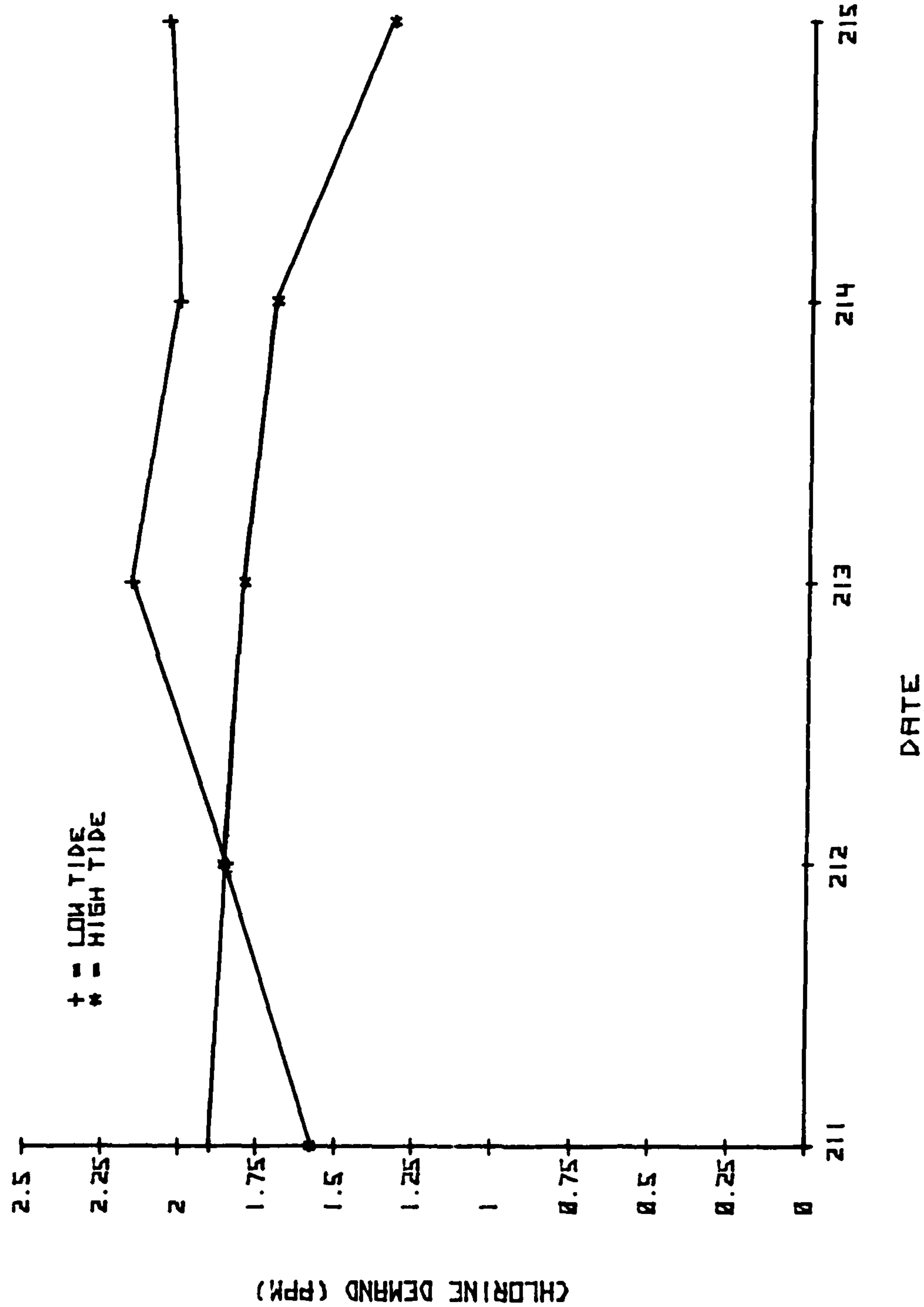

FIGURE 9. VARIATION IN CHLORINE DEMAND AT 5.0 MINUTES CONTACT TIME - 5-DAY PERIOD

analysis was also extensively modified from that of Fetkovich,[58] Fritsch et al,[38] and Boswell.[59] Changes to system software are documented in reports on software configuration and data analysis.[60 61]

Determination of fouling resistance was based on the transfer of heat from pipe walls to flowing seawater. Resistances to heat transfer were assumed to result from increases in the primary film located at the pipe/seawater interface and resistances in both the copper block and the copper block/pipe wall interface were assumed to be negligible. Thus, as fouling increased, changes in resistance were compared to baseline resistances established by the Wilson plot for the clean tube.[62]

Data acquisition began by heating each pipe until the pipe walls stabilized at a temperature slightly above that of flowing seawater. Heaters were then turned off and the pipe monitored for voltage decay of the cooling curve. From the raw cooling curve data, a time constant (λ) was calculated through linear regression of the natural logarithm of each data point. The cooling constant was used to calculate an uncorrected heat transfer coefficient (HUNCOR) using

$$\text{HUNCOR} = A + B\ (\ln\lambda) + C\ (\ln\lambda)^2 + D\ (\ln\lambda)^3$$

where A, B, C, and D are physical constants of the tube.[60] The HUNCOR was then corrected for heat losses other than that attributed to seawater flow (air loss/axial loss). Finally, to allow for comparisons between values of h calculated at different times, h was referenced to a nominal water temperature (70°F) (21°C) and flow velocity (6 feet/second) (1.8 m/sec) and yielded HRNOM. Fouling resistance (Rf) was calculated using:

$$\text{Rf} = ({}^{1}/\text{HRNOM}) - ({}^{H}\text{intercept} + {}^{H}\text{slope} {}^{*}(6{*}{*}(-0.8)).$$

[38] ibid.

[58] Fetkovich, J. F., "A system for Measuring the Effect of Fouling and Corrosion on Heat Transfer Under Simulated Conditions," Report COO-4041-10, Carnegie-Mellon University, December 1976.

[59] Boswell, David, "Data Acquisition System Design and Integration for the Ocean Thermal Energy Conversion Biofouling Test," David Taylor Naval Ships Research and Development Center Report (under preparation), 1980.

[60] Tuovila, S. M., "Data Analysis for Ocean Thermal Energy Conversion (OTEC)," Naval Coastal Systems Center Technical Memorandum TM 271-79, November 1979.

[61] Tuovila, S. M., "Software Configuration of Ocean Thermal Energy Conversion (OTEC) at Panama City Florida," Naval Coastal Systems Center Technical Memorandum (In preparation).

[62] Wilson, E. E., "A Basis for Rational Design of Heat Transfer Apparatus," American Society of Mechanical Engineers Transactions, 37, 1477 (1915).

Thus, measurements of fouling resistance were not made on individual heat transfer measurements of great accuracy but rather on changes in the heat transfer coefficient over the clean tube state.

Calibration of Heat Transfer Monitors (HTM)

As stated, all pipes were subjected to a Wilson plot before and, as circumstances allowed, after a biofouling experiment. The Wilson plot established the zero baseline for resistances other than biofilm accumulations.[62] These contact resistances are attributed to the interface between the pipe wall and heater block. The magnitude of this resistance was determined by measuring fouling resistance at a variety of flow velocities. The inverse of the velocity is plotted against fouling resistance and subjected to a linear regression. Line slope should be approximately 3.44×10^{-3} and the ideal intercept should be zero.[60] However, a deviation between the intercept and zero results that is a measure of contact resistance (i.e., nonbiological resistance) and is velocity independent.[63]

All available Wilson plots are attached as Appendix B. Plots are identified as to pipe condition (clean versus fouled), pipe material (see Table 2 for code numbers), slope, intercept, correlation coefficient, and date.

FIELD TESTS

Three major field tests were conducted by NCSC:

1. 1978-1979 experiment covering flow-driven brushes
2. 1979 experiment covering flow-driven brushes and recirculating sponge rubber balls
3. 1979-1980 experiment covering flow-driven brushes, recirculating sponge rubber balls, chlorination, and system combinations

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[60]ibid.

[62]ibid.

[63]Bird, S. P., 1980, "Uncertainties in Heat Transfer Measurements Obtained with the Carnegie-Mellon University Biofouling Device," In Condenser Biofouling Control, Eds: Gary, J. F., Jordon, R. M., Aitken, A. H., Burton, D. T., and Gray, R. H., Ann Arbor Science, Ann Arbor, MI, pp 185-204.

TABLE 2

CODE FOR HTM PIPE PURPOSES AND MATERIALS

Tube #	Purpose	HTM Material
1	Control, cleaned daily	Aluminum 5052*
2	Control, cleaned daily	Titanium
3	Control, freely fouling	Aluminum 5052
4	Control, freely fouling	Titanium
5	Flow-Driven Brush	Aluminum 5052
6	Flow-Driven Brush	Titanium
7	Recirculating Sponge Ball	Aluminum 5052
8	Recirculating Sponge Ball	Titanium

Odd tube numbers denote aluminum HTMs; even tube numbers, titanium HTMs.

* Aluminum 6061 in the 1978-79 experiment.

1978-1979 EXPERIMENT

In late August 1978, Argonne National Laboratory, the US Department of Energy's technical agent for OTEC, asked NCSC to assume overall responsibility for the biofouling countermeasures effort. The initial field experiment utilized system hardware and software devised by David Taylor Naval Research and Development Center for evaluation of flow-driven brushes. This field effort began in late September and ended in mid-December, a span of 62 days, with results presented at the OTEC Workshop on Biofouling and Corrosion.[64]

[64]Braswell, J. A., Lott, D. F., and Hedlicka, S. M., 1979. Preliminary Evaluation of Flow-Driven Brushes for Removal of Soft Biofouling from Heat Exchanger Tubes in OTEC Power Plants. In: Proceedings of the Ocean Thermal Energy Conversion (OTEC) Biofouling, Corrosion and Materials Workshop, January 8-10, 1979, Rosslyn, VA, ANL. OTEC-BCM-002, pp. 101-120.

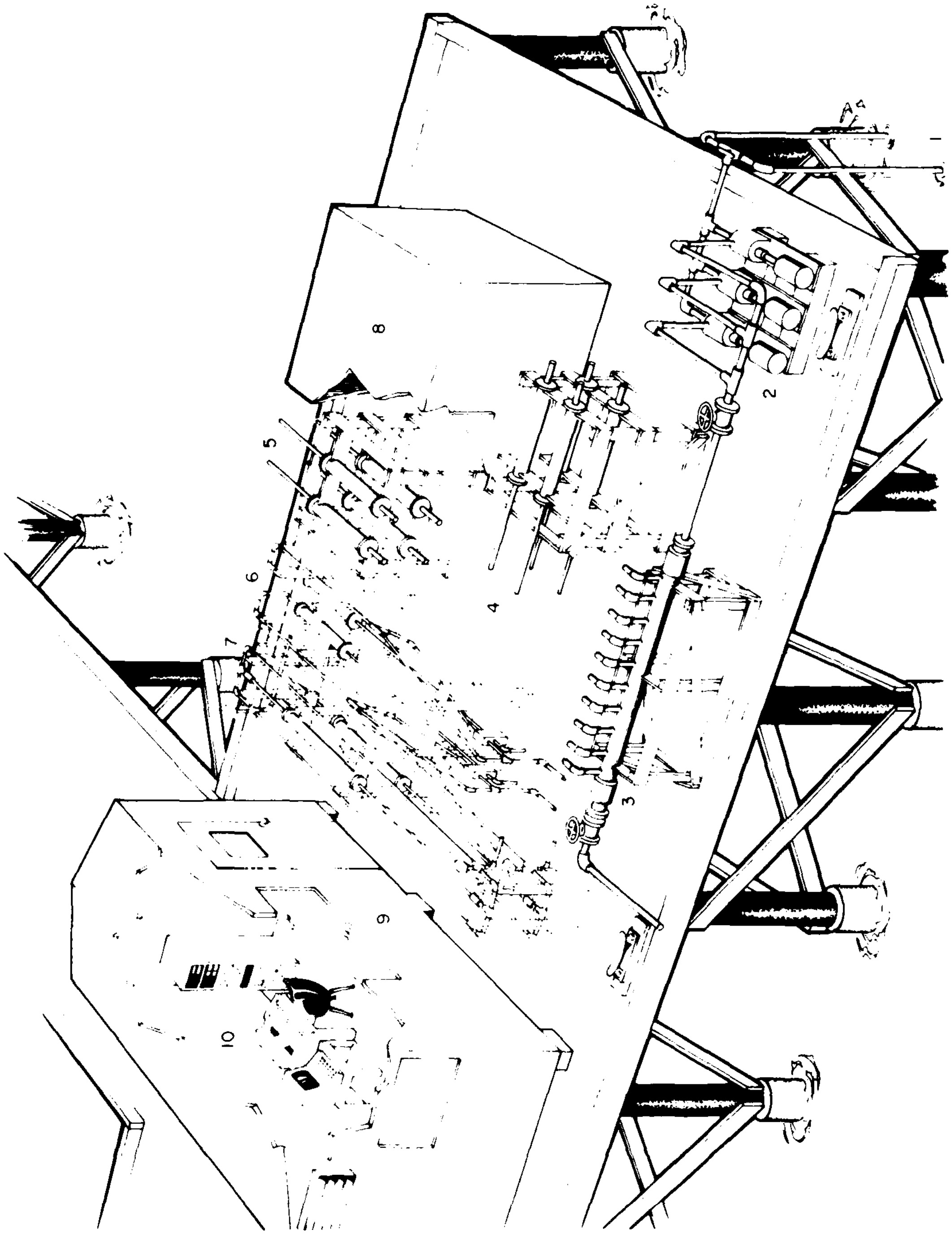

FIGURE 10. HEAT EXCHANGER CLEANING TEST FACILITY

Flow-Driven Brushes

Figure 11 is a diagram of the flow-driven brush system. The brush, slightly larger in diameter than the pipe, was contained in the downstream cage. Following the timing pulse, electrically operated valves were actuated which reversed flow, thereby driving the brush to the opposing cage (the upstream cage during normal flow) where it remained for 15 seconds. Thereafter, the valves cycled back to their normal position, returning the brush to the downstream cage. Flow reversal followed by normal flow thus provided a single cleaning cycle.

The initial test of flow-driven brushes evaluated the commercially recommended (28 mm bristle diameter) brush operating on an 8-hour cleaning cycle. The brush used is seen in Figure 12.

Controls

Four control units, fed simultaneously from the same seawater header, were used in all three experiments. Each unit consisted of an aluminum or titanium pipe equipped with a flowmeter and HTM. One aluminum and one titanium control unit were cleaned daily, while a second pair was allowed to foul freely. These controls thus represented the extremes in Rf values.

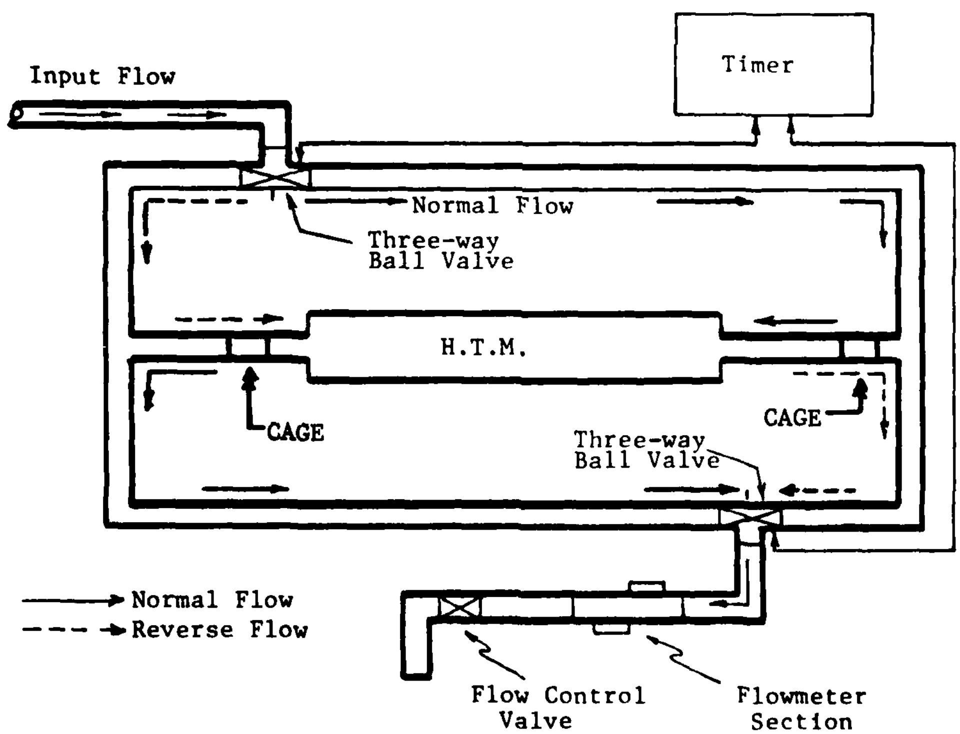

FIGURE 11. FLOW-DRIVEN BRUSH CLEANING SYSTEM

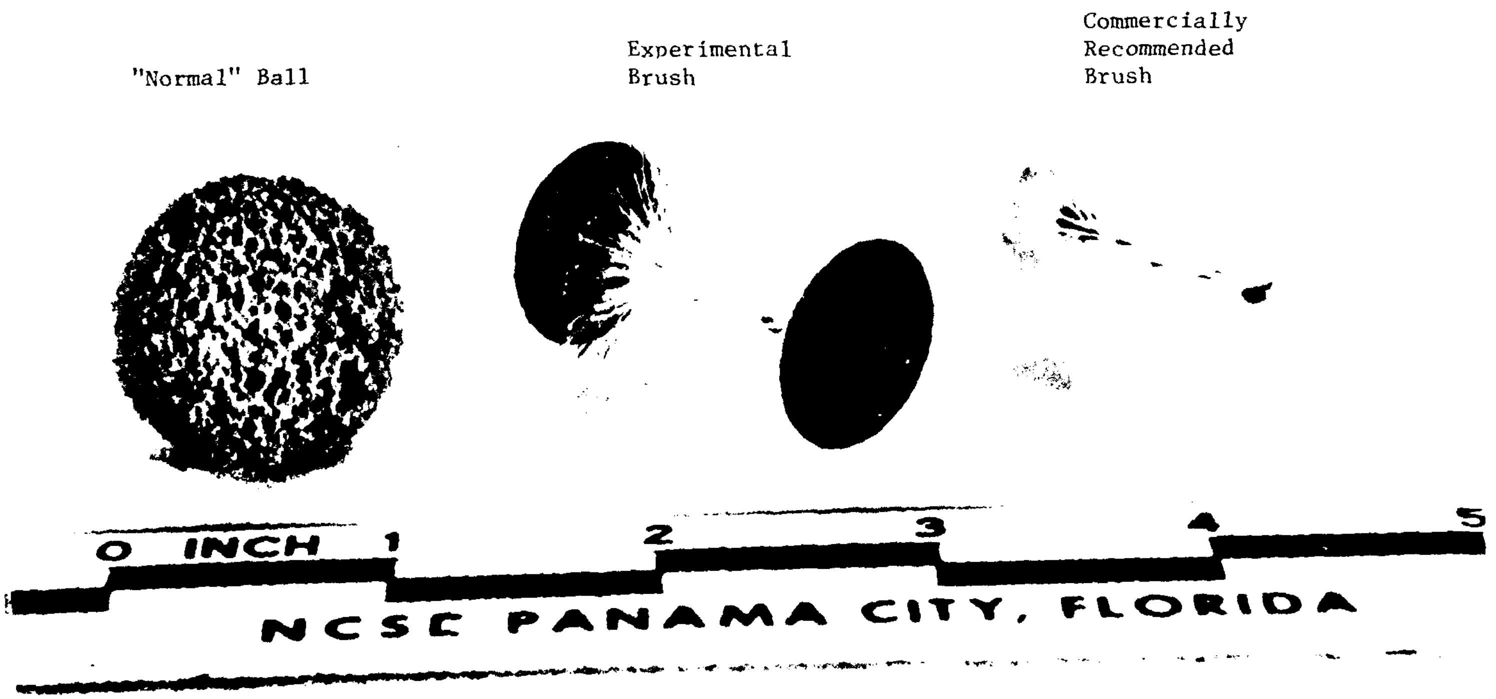

FIGURE 12. 28-MM SPONGE RUBBER BALL AND BRUSHES

The control pair that was cleaned daily provided the zero baseline and served as an internal check of the data-gathering system. The Rf value of this control seldom exceeded 1.0 X 10^{-4} ft^2-hr-°F/Btu. Cleaning was affected by 20 passes of the nylon-bristle bottle brush on an extended handle. The brush was designed to fill the tube tightly to exert a considerable shear force on the tube walls.

The second pair of controls was allowed to foul freely. This control was used to determine fouling rate and was not cleaned until a Rf of 5.0 X 10^{-4} ft^2-hr-°F/Btu was observed. At that time, HTMs were cleaned and returned to service.

1979 EXPERIMENT

The 1979 experiment began on 10 May 1979 and ended on 8 July 1979. The flow-driven brushes and recirculating sponge rubber balls were tested during this period. Hardware problems prevented any tests of chlorination. The 60-day test period provided 13,556 cooling curves for analysis and results were presented at the Sixth OTEC Conference.[65]

Flow-Driven Brushes

The system tested was essentially the same as used in the previous experiment except that the brush was operated on a reduced cycle interval of 4 hours. In addition, the effectiveness of brush replacement on reducing Rf was explored.

Recirculating Sponge Rubber Balls

The system for recirculating sponge rubber balls used unidirectional flow by peristaltic pumps as shown in Figure 13.

Ball movement was controlled by a variable timer. When the specified cycle interval had lapsed, the timer started the peristaltic pump which drove a single ball into the HTM loop, through the HTM, and into the ball catcher. The catcher diverted the ball past the optical sensor which simultaneously cut off the peristaltic pump and reset the timer. This system was used from 10 May to 25 May. A failure of peristaltic pumps necessitated a new system for ball circulation. On 7 June the ball evaluation was restarted using a new system

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[65]Lott, D. F. and Tuovila, S. M., "Fouling Countermeasures - Status of Two Mechanical Cleaning Systems and Chlorination," Proceedings of the Sixth OTEC Conference, Washington, DC, June 1979.

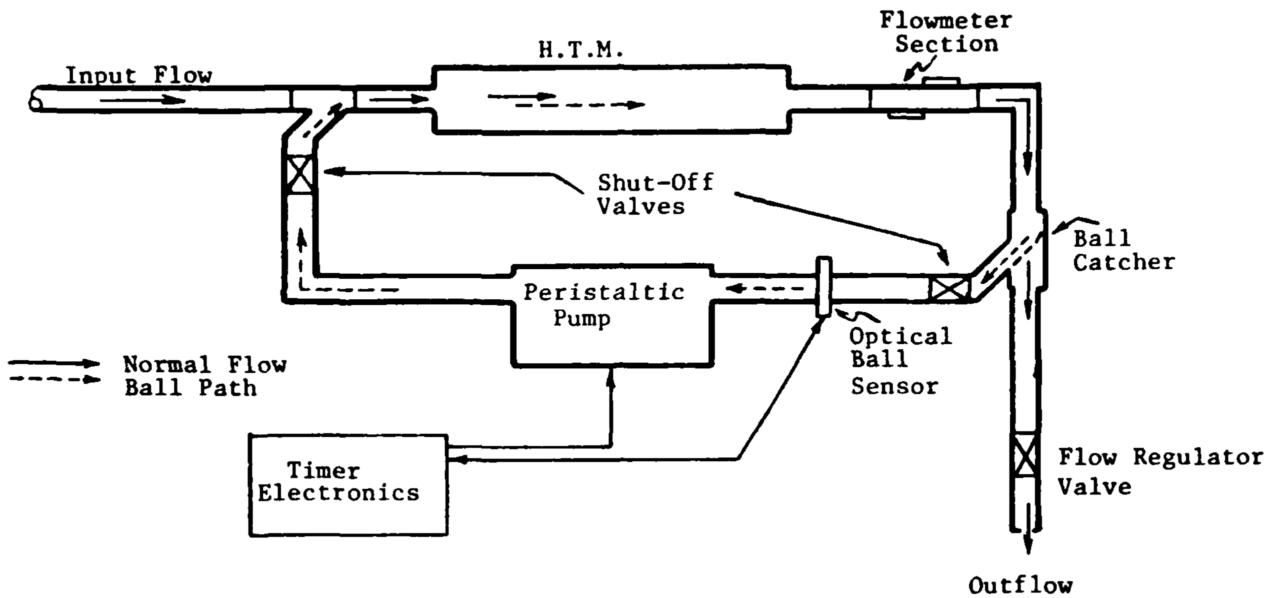

FIGURE 13. PERISTALTIC PUMP SYSTEM FOR BALL CIRCULATION

for ball movement designed by Argonne National Laboratory (ANL) (Figure 14) and with electronics supplied by NCSC. The system controller was a variable timer that provided the pulse triggering the movement of electrically operated valves to the release position. Flow pressure, greater than that in the HTM loop, drove the ball into the HTM loop, through the HTM, and past an optical sensor. The optical sensor caused the valve to return to its original (i.e., catch) position and reset the timer. The ball, meanwhile, was shunted into a bypass loop by a strainer. Finally, water flow through the valve caused the ball to move into the valve in preparation for the next cleaning cycle.

Tested during this period were 28 mm "hard" balls and a 15-minute cleaning cycle.

Controls

Controls were the same as those used in the 1978-1979 experiment.

1979-1980 EXPERIMENT

The 1979-1980 experiment began on 18 September 1979 and ended on 31 March 1980. This experiment evaluated the systems described below as well as combinations of each mechanical system with chlorination. The experiment provided

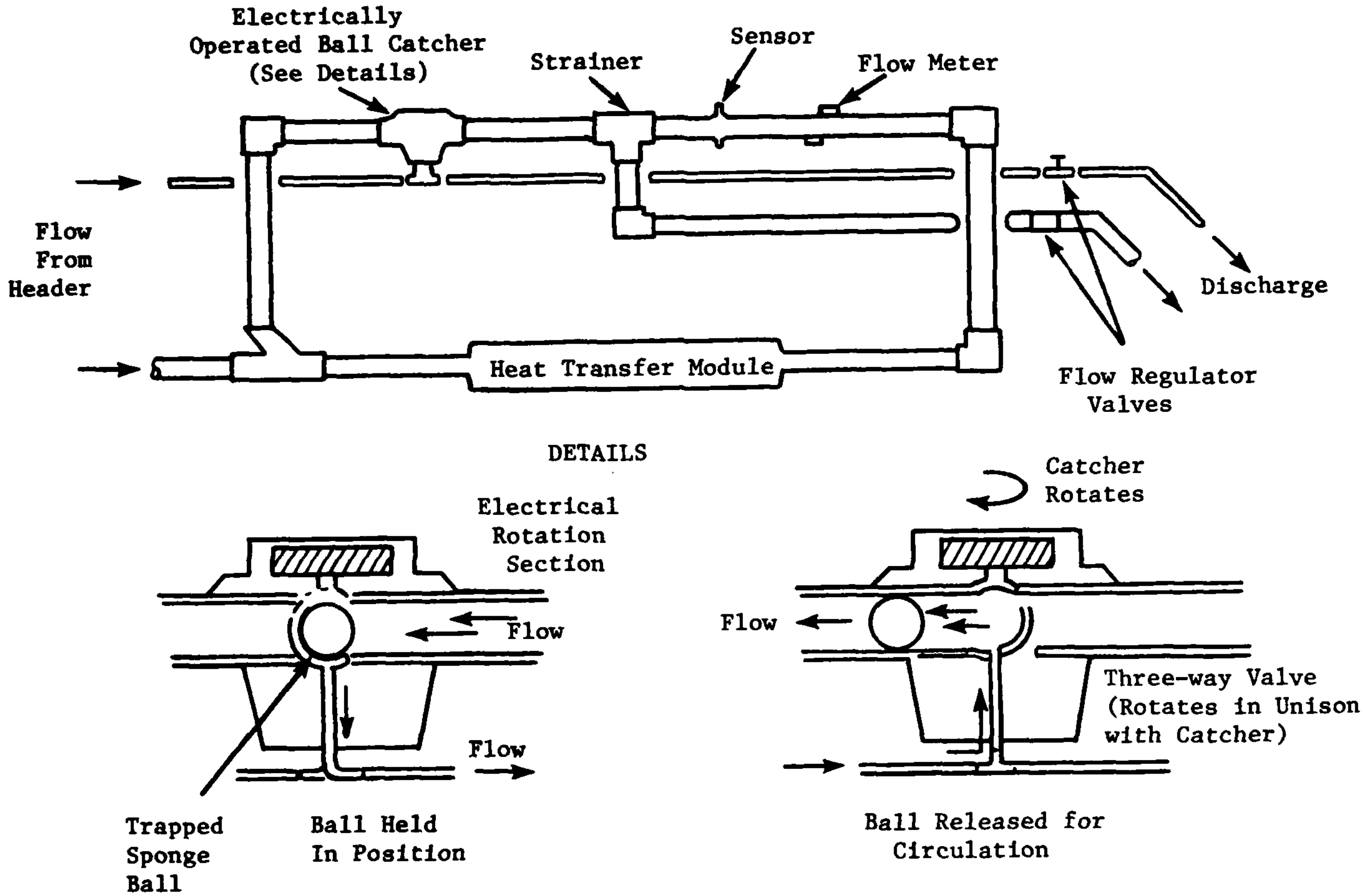

FIGURE 14. ANL PRESSURE SYSTEM FOR BALL CALCULATION

an unbroken series of tests over the 195-day period and resulted in 56,479 cooling curves. Major portions of the work were presented at the Seventh OTEC Conference.[66]

Flow-Driven Brushes

The brush system pictured in Figure 11 was modified from that described previously. The major change was an improved brush catcher housing (Figure 15a) that eliminated low flow velocity areas (Figure 15b). The constriction that resulted on the HTM ends made it necessary to filter the flow so as to reduce the marine biomass prevalent in the influent from St. Andrew Bay. The system used flow reversal to drive a single brush back and forth through a heat transfer unit. Cleaning interval and brush parameters such as bristle composition, length, and number were selected for testing. Since a 4-hour interval is the minimal practical interval between cleaning cycles by a full-scale plant,[44] initial tests used this 4-hour cycle and varying brush parameters.

Selection of a brush for testing was based on 1978-1979 experimental results. Those results indicated acceptable Rfs could be obtained with the commercially recommended brush (28 mm diameter bristle) in the titanium pipe operating on either 4- or 8-hour cleaning cycles. The aluminum pipe, however, demonstrated poor Rfs for all cleaning cycles tested. Although there are few brush types available for testing, Water Services of America supplied some experimental (28 mm diameter bristle) brushes that differed from the commercial brush in bristle composition, stiffness, and number of bristles. Late in the test program, very limited testing was done with a 29 mm diameter brush that differed from the experimental brush solely in brush diameter.

Recirculating Sponge Rubber Balls

Many deficiencies were noted in the previous tests of recirculating sponge rubber balls. Problems such as failure of the peristaltic pumps, failure of flexible tubing within the pumps, electronics failures, and ball distortion by the pumps prevented an evaluation of the cleaning system (balls).

Most of those problems identified in the previous tests were eliminated by redesigning the system to deliver unidirectional flow for ball movement but providing a mechanism for ball injection and capture (Figure 16). Following a timing pulse, relays were activated which drove a plunger containing the sponge rubber ball into the water flow. The ball was forced into the Heat Transfer Monitor (HTM) past the optical sensor which simultaneously reset

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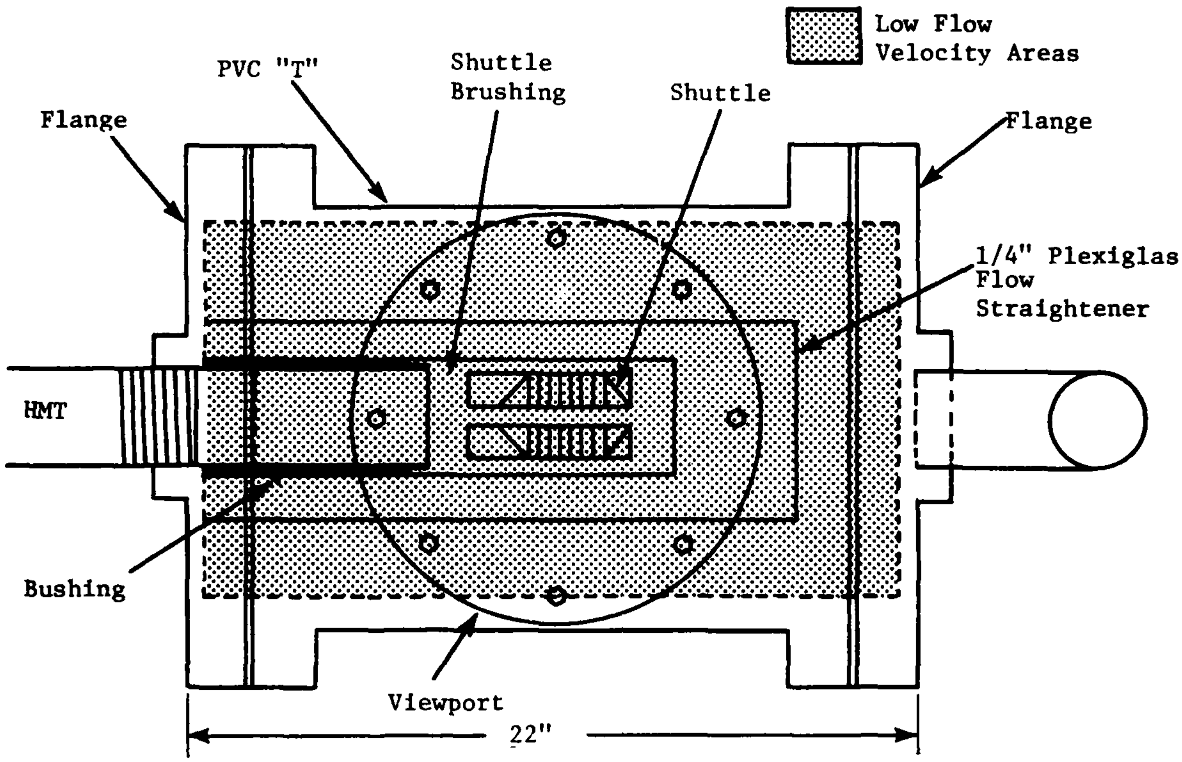
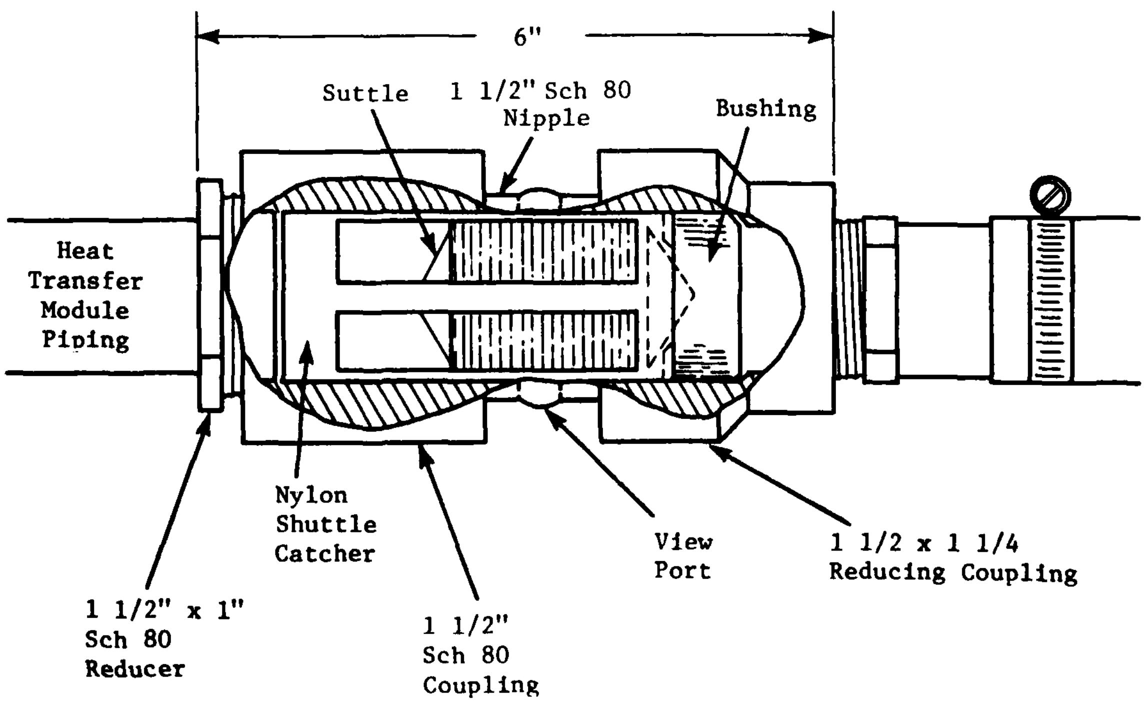
[44]ibid.

[66]Lott, D. F. and Tuovila, S. M., 1980, "In-Situ Cleaning of OTEC Heat Exchangers," Proceedings of the Seventh OTEC Conference, Washington, DC, June 1980.



(A) UNMODIFIED BRUSH CATCHER



(B) MODIFIED BRUSH CATCHER

FIGURE 15 MODIFICATION TO FLOW-DRIVEN BRUSH SYSTEM

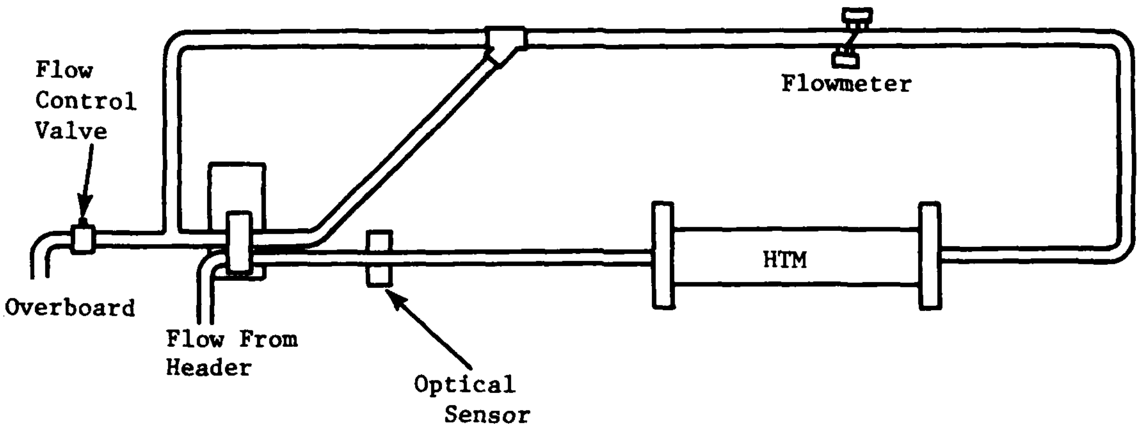


FIGURE 16. NCSC MECHANICAL SYSTEM FOR BALL CIRCULATION

the timer, incremented the counter, and moved the plunger to catch position. In the cleaning system tested, a cleaning cycle consisted of the passage of *a single ball through the HTM.*

Parameters tested include ball diameter, ball stiffness, and cycle interval. The minimum time between ball cycles was determined to be 15 minutes.[46] In contrast to 1978-1979 test results, the commercially recommended ball (28 mm "medium" ball for 1-inch pipe) was not used in favor of a 29 mm "soft" ball that increased shear forces at the pipe wall.

Chlorination

The initial test system featured continuous chlorination of identical parallel loops for aluminum and titanium pipe serviced by a single chlorine generator (Figure 17). Test results, however, showed insufficient flow available for continuous chlorination. This problem was eliminated by providing a system for intermittent chlorine dosing (Figure 18). Testing of intermittent dosing was severely limited by tests performed in conjunction with the mechanical systems as well as biological tests. These problems resulted in a long-term test of a single chlorine dosage for each material.

[46]ibid.

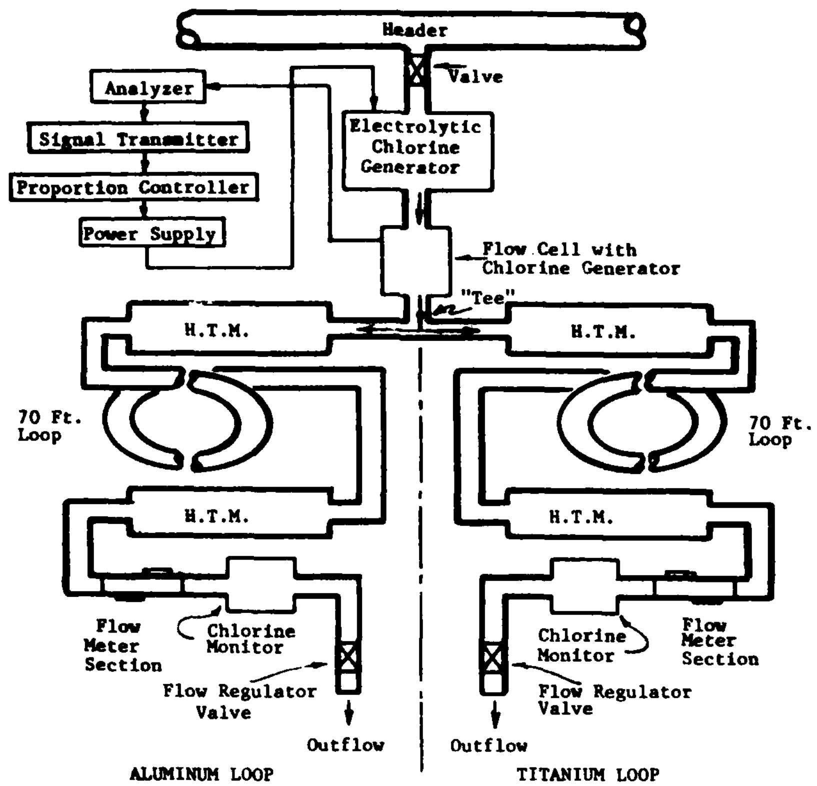


FIGURE 17. CONTINUOUS CHLORINATION SYSTEM

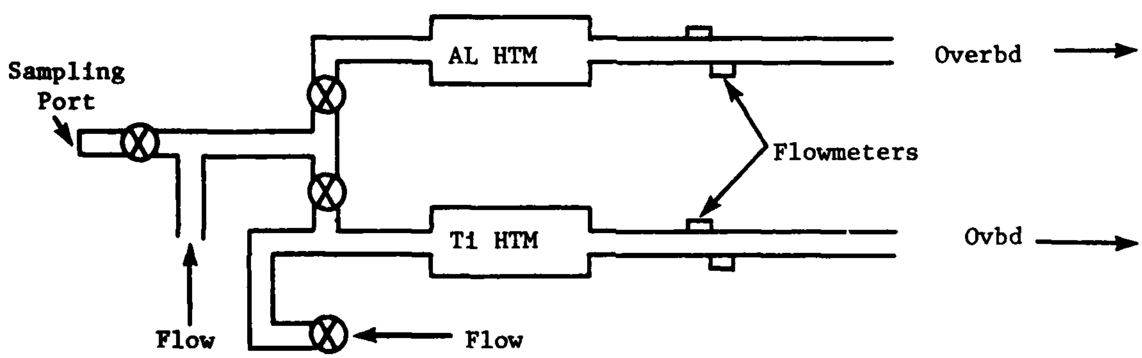


FIGURE 18. INTERMITTENT CHLORINATION SYSTEM

Controls

The controls were identical to those utilized in the 1978-1979 tests. In addition, a number of biological tests were performed using these pipes and are reported elsewhere.[67 68 69]

RESULTS AND DISCUSSION

Results are presented as date (or days) versus fouling resistance (Rf) values for each HTM tested. On all Rf figures, the target Rf of 0.0001 ft^2-hr-°F/Btu equals 1.0 R Foul *(E-04). Each Rf plotted represents the mean daily average for that day. Each average was calculated from cooling curves that fell within data specifications such as low flow rate standard deviations, good curve fits, and proper operating conditions.

The results discussed below were taken from the Sixth and Seventh OTEC Conferences[65 66] as well as the ANL Biofouling and Corrosion Workshop.[64] In addition, details not previously available have been included. This report thus represents a summary of all field tests conducted by NCSC in support of OTEC and serves as a final report.

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[64]ibid.

[65]ibid.

[66]ibid.

[67]White, D. C., Bobbie, R. J., Nickels, J. S., Parker, J. H., Smith, G. A., Davis, W. M., Lott, D. F., and Benson, P. H., 1980b. Assay and Correlation Between Mirobial Fouling and OTEC Cleaning of Surfaces Exposed to Seawater. Extended Abstracts of Seventh Ocean Energy Conference, Washington, DC, June 1980.

[68]Bobbie, R. J.; White, D. C.; and Benson, P. H., 1980, "Biochemical Analysis of the Response of the Marine Microfouling Community Structure to Cleaning Procedures Designed to Increase Heat Transfer Efficiency." Proceedings of the Fifth Int. Congr. of Marine Corrosion and Fouling, Barcelona, Spain, pp. 391-400.

[69]White, D. C., 1980, "Assays of Microfouling Community in OTEC Simulation System Modified to Include Effects of Cleaning Techniques on the Biomass, Physiological State and Population Structure of the Primary Microbial Biofouling of the OTEC Simulation System." Final Report ANL Contract No. 31-109-38-4502.

RESULTS FOR 1978-1979 EXPERIMENT

Flow-Driven Brushes

In this, the initial test of flow-driven brushes, the manufacturer approved all test procedures both before and after tests. However, several factors affected NCSC tests that may not apply to potential OTEC sites. First, both kinds and quantities of fouling organisms at the test site may differ significantly from those of potential OTEC sites. Presumably, the bacterial genera which constitute the primary film formers at these flow rates (6 feet/second) would not differ significantly.[70] However, the concentration of micro-organisms is probably much greater at this shallow-water, inshore test site than at a potential OTEC deep-water intake. Secondly, the design of the test apparatus led to low velocity areas near the test pipe. This resulted in substantially increased macrofouling, which directly affected the operation of the brush cages and contributed to the volume and composition of debris passing through the tubes. Though some low velocity areas will inevitably occur in the design of an OTEC plant, their proximity to and influence upon the heat exchanger tubes should be less dramatic than the oyster-dominated communities in the NCSC test apparatus.

The buildup of debris from these macrofouling communities completely stopped the movement and cleaning action of the brush in the aluminum pipe. Fortunately, the obstruction occurred near the end of the experiment and valid results were obtained for a suitable long test period (approximately 2 months). However, both brushes exhibited an accumulation of debris that would not be expected in a normal OTEC operation.

Despite the accumulation of foreign material in the brushes, both systems showed a substantial degree of cleaning effectiveness (Figure 19 and Figure 20). In the titanium pipe, the flow-driven brush (28-mm brush/8-hour cycle) satisfied the manufacturer's claim, and maintained a fouling resistance near 0.0001 ft^2-hr-°F/Btu throughout most of the test period (Figure 19). Visual inspection and borescope observations of this pipe at the end of the 3-month test period confirmed that the pipe was shiny and clean on the interior.

The brush (28-mm brush/8-hour cycle) was somewhat less effective for the aluminum pipe (Figure 20). Even before the brush became stuck in its nylon cage, fouling resistance in the aluminum pipe began to exceed the acceptable limit of 5.0×10^{-4} ft^2-hr-°F/Btu. Visual inspection and borescope observations of this tube revealed a noticeable film at the end of the test. Even after hand brushing and chemical cleaning (sodium hydroxide followed by nitric acid), the interior of this tube exhibited a hard scale. This residue may indicate that fouling resistance in the aluminum tube was due primarily to inorganic deposits.

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[70] O'Neill, T. B., Personal communication, 1977.

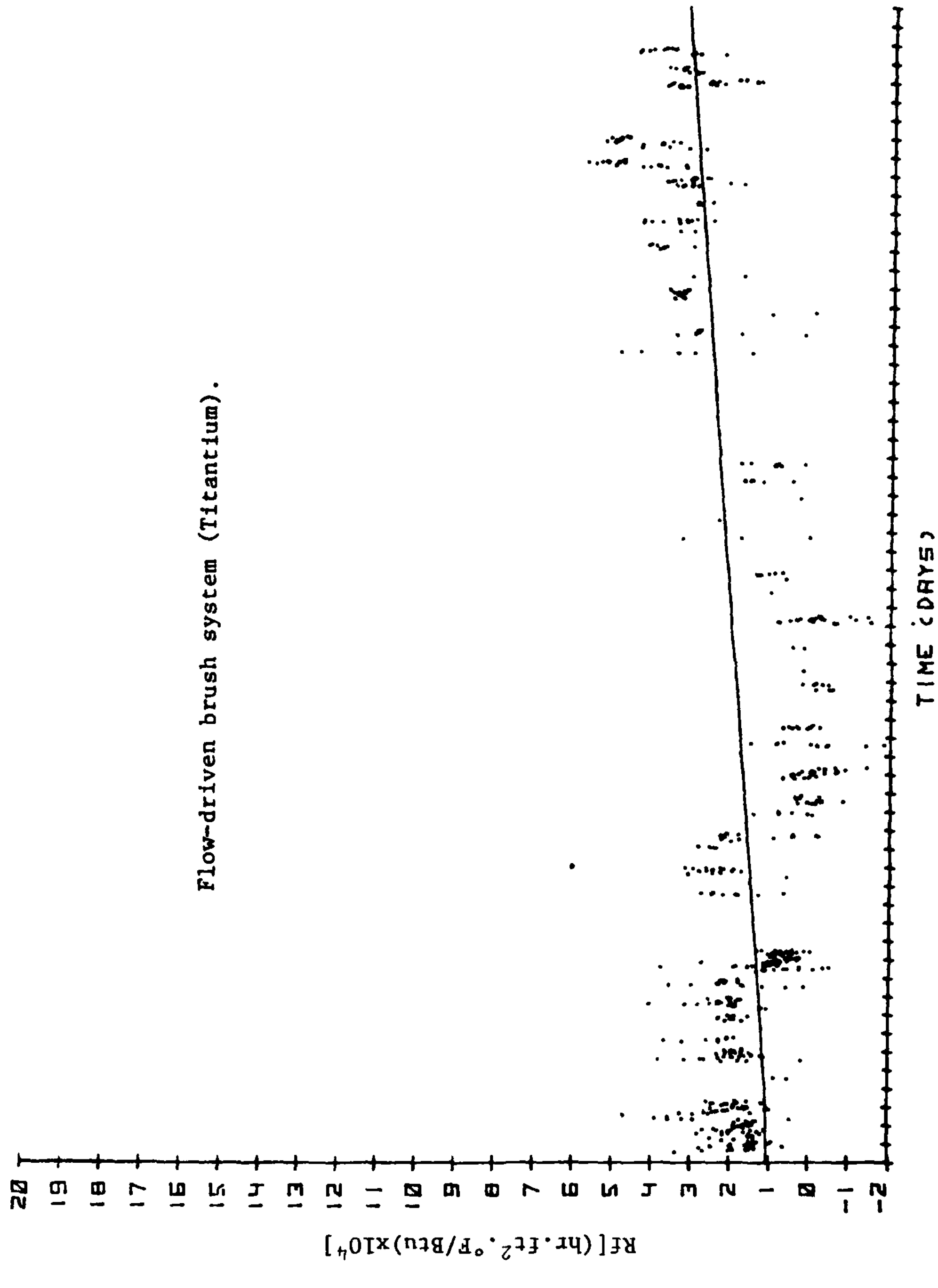

FIGURE 19. THERMAL RESISTANCE (Rf) VS TIME FOR TUBE 6 (TITANIUM)

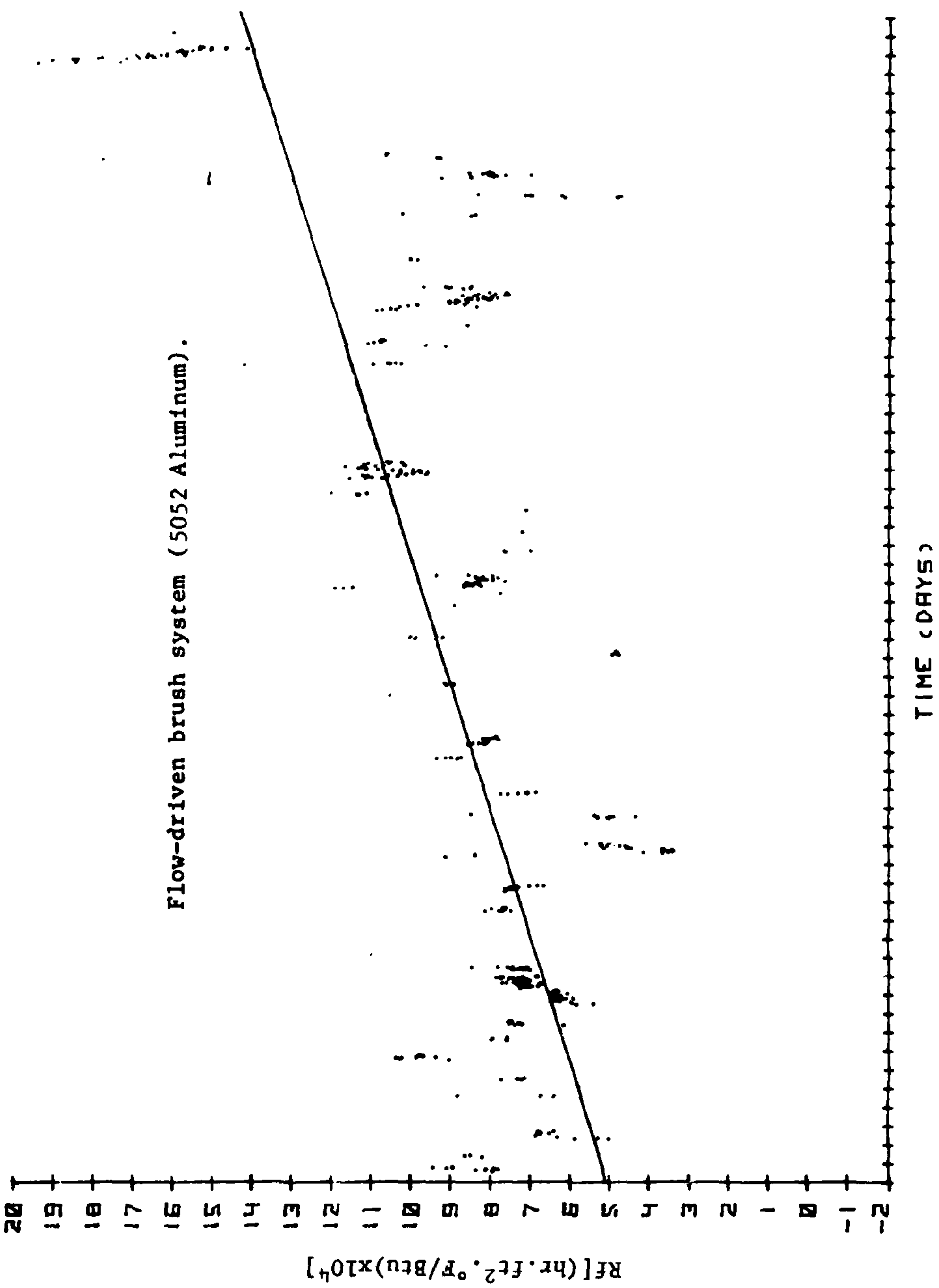

FIGURE 20. THERMAL RESISTANCE (Rf) VS TIME FOR TUBE 5 (ALUMINUM)

Although the flow-driven brush system performed well in this evaluation, there was evidence of brush fatigue even at the end of this relatively short test period. Measurements of bristle length before and after the test showed an average decrease of 0.014 inch (0.34 mm) in bristle length. Microscopic examination revealed a distinct flattening of the bristle ends due to wear. Thus, bristle wear rate will become a significant design factor in the effectiveness of this brushing system.

Controls

The strongly negative values shown in Figure 21 for aluminum pipe are believed to result, in part, from inadequate Wilson plot parameters. Thermal resistance between the seawater flowing through the tubes and the temperature sensor in the tube wall is estimated from a Wilson plot. The method is generally accurate but has certain limitations for fouling studies. In addition to the problems cited by Fritsch et al,[38] initial formulation of the plot may suffer from the amount and accuracy of data available. In addition, the vigorous daily cleaning to which this aluminum tube was subjected may have removed oxide layers from the tube wall. This repeated scouring of the pipe surface may have resulted in an actual decrease in the thermal resistance of the pipe after the Wilson plot was taken. Hence, values based upon the original plot have become negative.

Cleaning of the aluminum pipe was abandoned late in the test period to study the problem of negative data for the tube. Fouling resistance values then increased considerably but remained negative throughout the study. This evidence indicated that both wall scouring and a faulty Wilson plot were responsible for offsetting Rf values (Figure 21) to yield negative values.

Conversely, Figure 22 (the titanium pipe) shows results expected for a tube cleaned daily. The fouling resistance of this tube was maintained near 0.0001 ft^2-hr-°F/Btu for most of the study period. This was well within the range sought for this experimental control (<0.0005 ft^2-hr-°F/Btu). Removal of an oxide layer, which is believed to be partially responsible for the negative data for aluminum (Figure 21), apparently was insignificant in the vigorously cleaned titanium tube.

It is significant that a fouling resistance indicative of a residual thermally resistant layer was maintained despite the vigorous cleaning. The nature of this layer was not determined. The pipe wall appeared clean upon visual inspection and in borescope photographs taken after the test. It is probable that the material was mostly inorganic since it is unlikely that much biological material could have remained after such vigorous cleaning.

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[38] ibid.

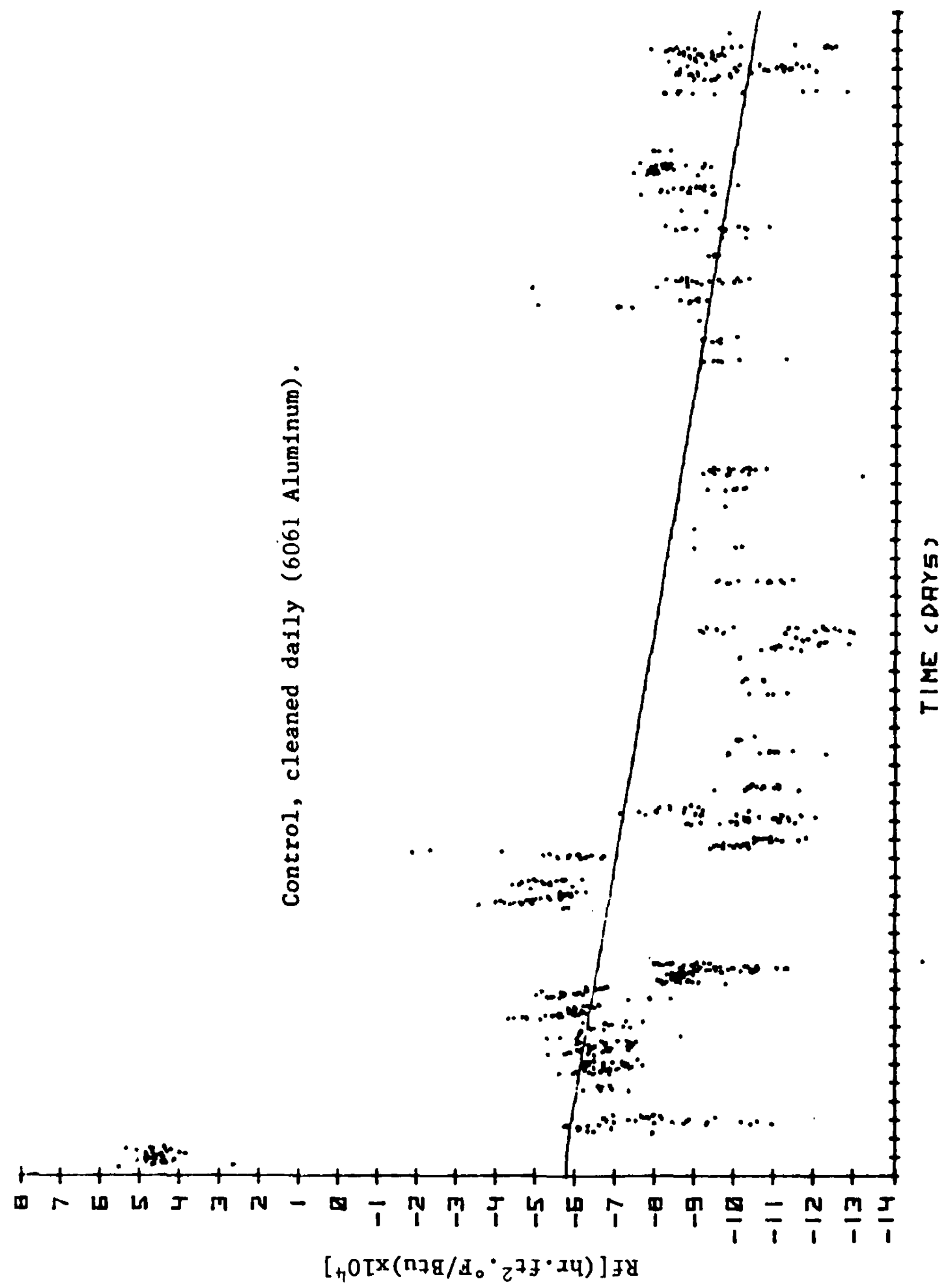

FIGURE 21. THERMAL RESISTANCE (Rf) VS TIME FOR TUBE 1 (ALUMINUM-CONTROL)

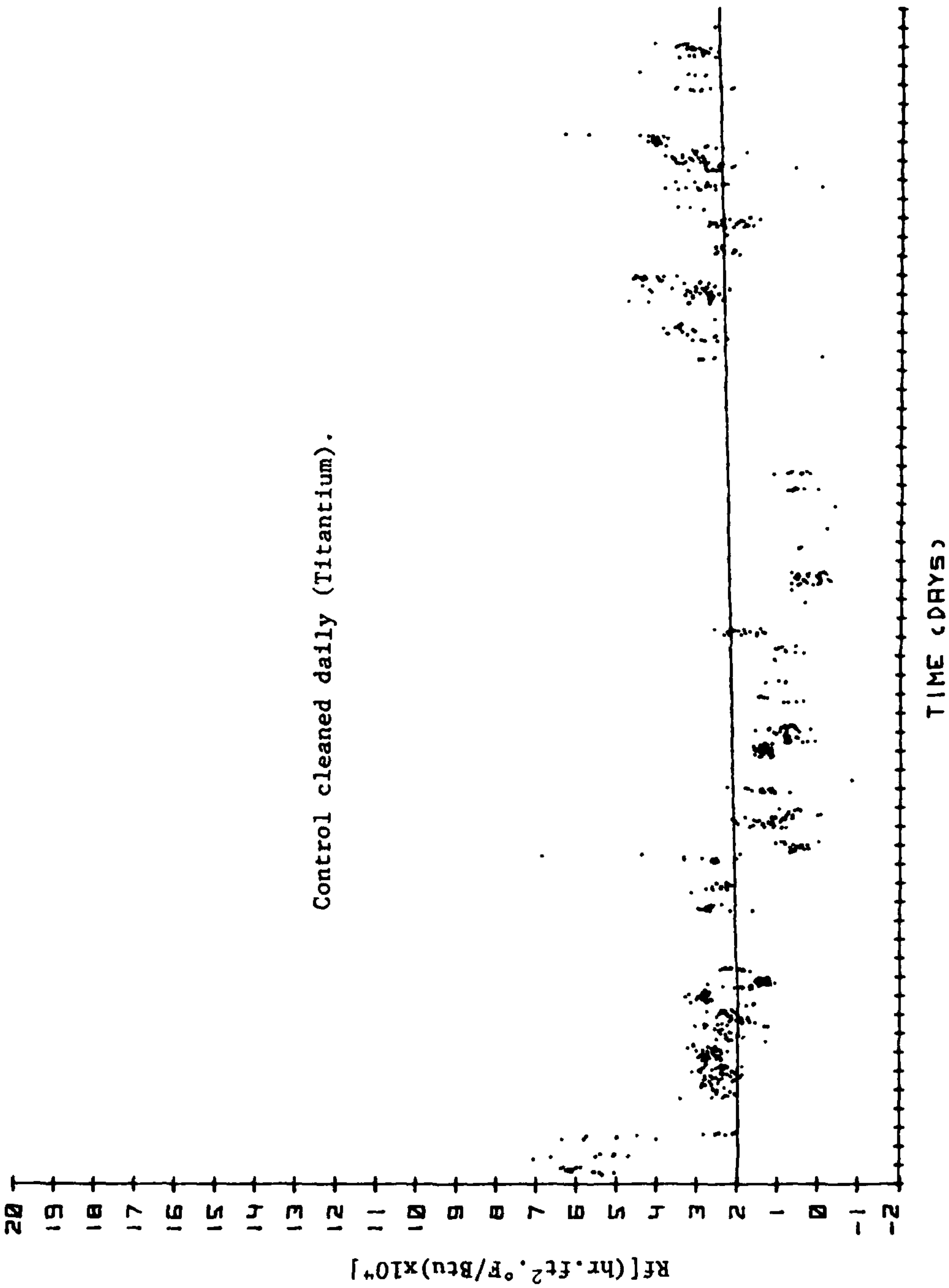

FIGURE 22. THERMAL RESISTANCE (Rf) VS TIME FOR TUBE 2 (TITANIUM-CONTROL)

Figures 23 and 24 (aluminum and titanium, respectively, the free-fouling controls) also show results which were close to those anticipated. The fouling resistance increased to high levels and a thermally resistant layer was maintained throughout the test period. Variations in the fouling resistance occurred suddenly, indicating occasional sloughing off of portions of the fouling film.

A comparison of aluminum and titanium pipe is of interest since it appeared that titanium fouled more rapidly and to a greater extent than did aluminum. This observation is confirmed by the biological data as well as by measurements of thermal resistance. Results obtained over the 3-month period generally indicate higher values for alkaline phosphatase, total organic carbon (TOC), and adenosine triphosphate (ATP) from titanium pipe sections. However, on test completion, substantial soft fouling was seen in each pipe material and appeared on borescope photographs.

COMMENT

Following this experiment, a detailed data analysis was undertaken to explain the unusual plots seen as Figures 19 through 24. The plotting of individual data points should result in a linear increase or decrease in Rf. The vertical nature of plotted points was indicative of a problem.

Through the efforts of Glenn Popper (ANL), Glenn Granneman (formerly of Carnegie-Mellon University), and Susan Tuovila (NCSC), a problem was identified in stepping between channels by the flowmeter which was eliminated in later tests. These initial data are therefore questionable.

RESULTS OF 1979 EXPERIMENT

Flow-Driven Brushes

This test of flow-driven brushes consisted of two parts. The first involved an evaluation of the commercially recommended brush (28 mm bristle diameter) operating on a 4-hour cleaning cycle. At the end of 34 days (13 June), the aluminum unit (Figure 25) had an Rf of 3 X 10^{-4} ft^2-hr-°F/Btu. This unit also showed a gradually increasing trend in Rf throughout the test period. Fouling resistance in the titanium unit, on the other hand, oscillated between 0.0 and 1.0 X 10^{-4} ft^2-hr-°F/Btu throughout the test period regardless of brush condition (Figure 26).

In contrast to information available in the literature,[44] brush wear is definitely a factor for design consideration. At the end of 34 days,

[44]ibid.

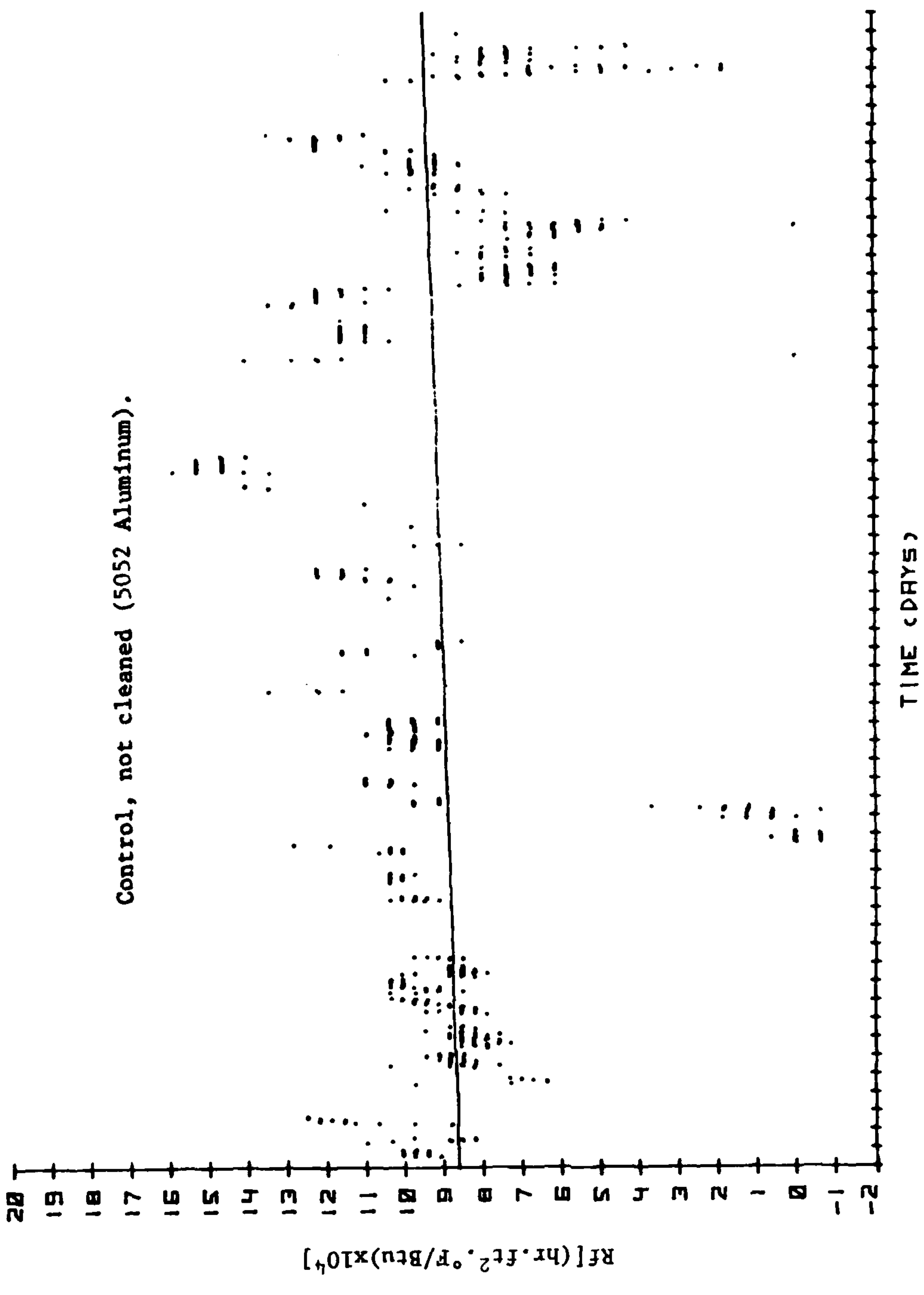

FIGURE 23. THERMAL RESISTANCE (Rf) VS TIME FOR TUBE 3 (ALUMINUM-FREE FOULING)

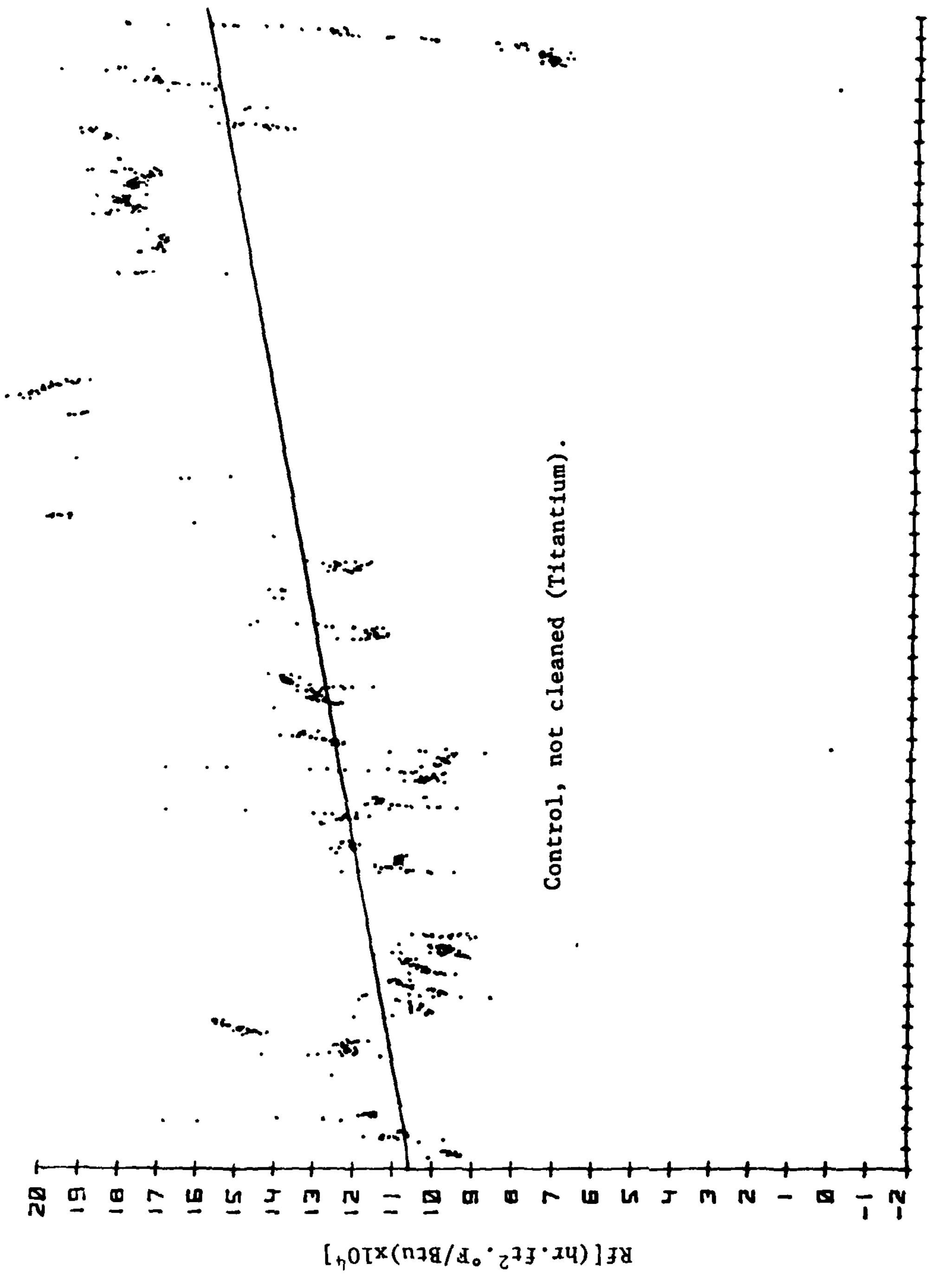

FIGURE 24. THERMAL RESISTANCE (Rf) VS TIME FOR TUBE 4 (TITANIUM-FREE FOULING)

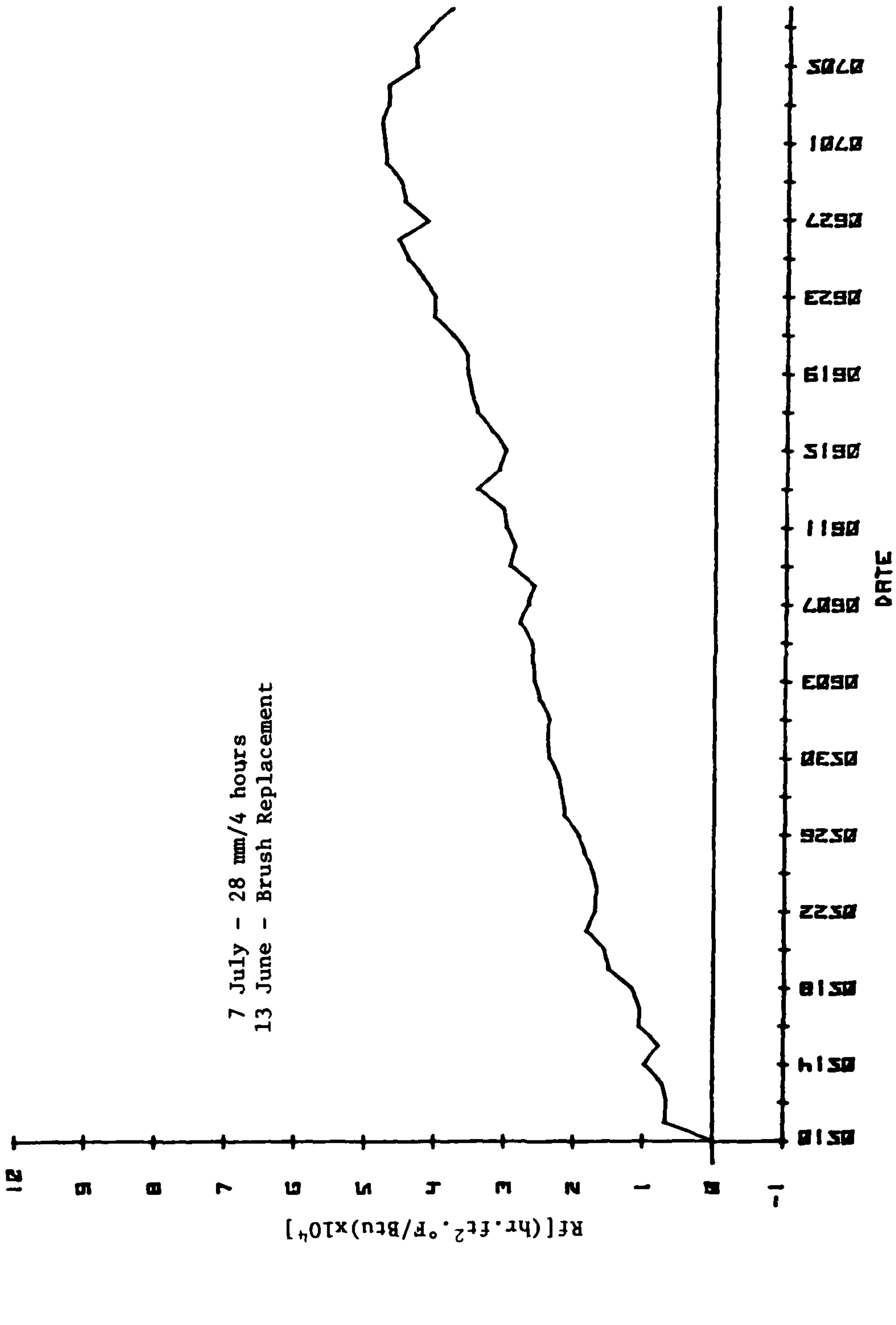

FIGURE 25. FOULING RESISTANCE VERSUS DATE IN THE ALUMINUM FLOW DRIVEN BRUSH CLEANING SYSTEM

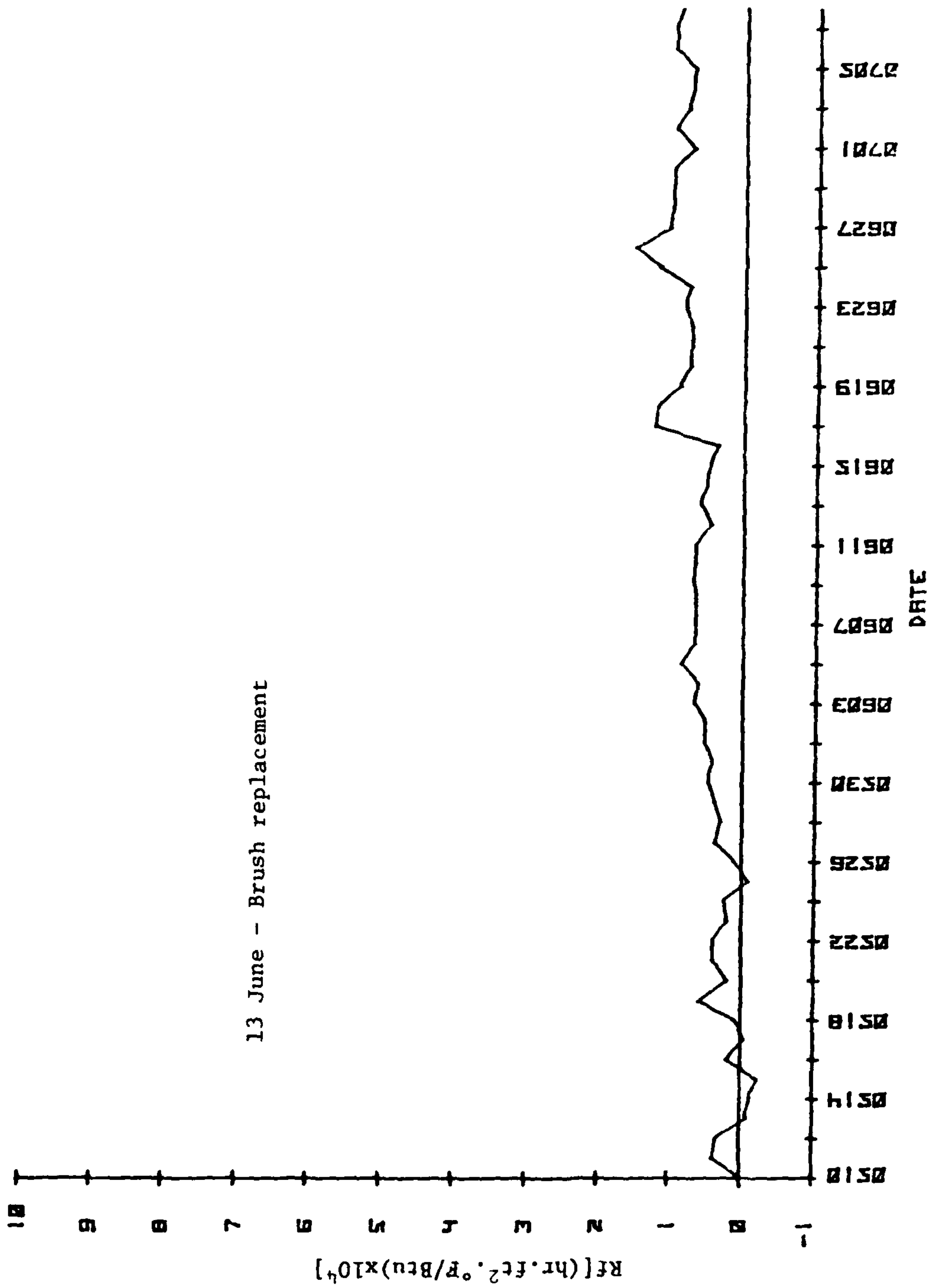

FIGURE 26. FOULING RESISTANCE VERSUS DATE IN THE TITANIUM FLOW DRIVEN BRUSH CLEANING SYSTEM

the aluminum pipe (Alloy 5052) showed a loss of 0.098-inch brush bristle length (241 passes) while the titanium pipe showed a loss of 0.126 inch (246 passes). This represents a decrease in bristle length of 9.5 percent and 11.6 percent, respectively, and reproduced previous results (1978-1979 experiment).

The second part of this test was a logical extension of the normal operation of the cleaning system. At various times, brushes have to be replaced since wear on bristle length will directly affect system performance. Therefore, new brushes were placed in the system on 13 June. This mimicked system maintenance (brush replacement) during normal operation and did not involve cleaning the pipes. Results indicated that in both pipe materials Rf showed an initial decrease but quickly re-established itself to previous levels. Brush replacement has limited value for lowering Rf as brushes wear out.

In general, the aluminum pipe showed an increasing trend in Rf over the 60-day test period. A decrease was observed in Rf toward the end of this test, but it is not known whether the decrease was transient or, in fact, a real long-term reduction. In the titanium pipe, Rf remained between 0 and 1.0×10^{-4} ft^2-hr-°F/Btu although Rf showed a very slow increasing trend over the test duration. It appears that a longer test might be required to determine the nature of the sharp increase in Rf toward the end of the test.

Recirculating Sponge Rubber Balls

Performance of the 28 mm "hard" ball is shown in Figure 27 for aluminum and Figure 28 for titanium pipe. For the period 10 to 24 May, ball recirculation was by peristaltic pumps. With this system, the aluminum pipe showed a gradual increase in Rf to 2.0×10^{-4} ft^2-hr-°F/Btu in 2 weeks. Results in the titanium tube were not so clear. Oscillations in the curve represent problems with ball movement that occurred in this test system. Peristaltic pumps were inadequate for evaluation of ball cleaning effectiveness. During the 14-day period, there were five major problems preventing ball movement and affecting cleaning performance. Tests were finally terminated when the pump motor burned out (24 May).

At least two candidate systems were evaluated to replace the peristaltic pumps for recirculating the sponge balls. The system selected was designed by A. P. Gavin, Argonne National Laboratories, and was similar to those proposed for OTEC-1.

On 7 June, a test with the 28 mm "hard" ball operating on a 15-minute cycle was initiated using the ANL designed system. Results are seen in Figure 27 (Alloy 5052) and Figure 28 (Ti). Although subject to pertubations, the aluminum pipe showed a gradual increasing trend in Rf throughout the 34-day test period. At the end of 34 days, Rf approached 2.5×10^{-4} ft^2-hr-°F/Btu.

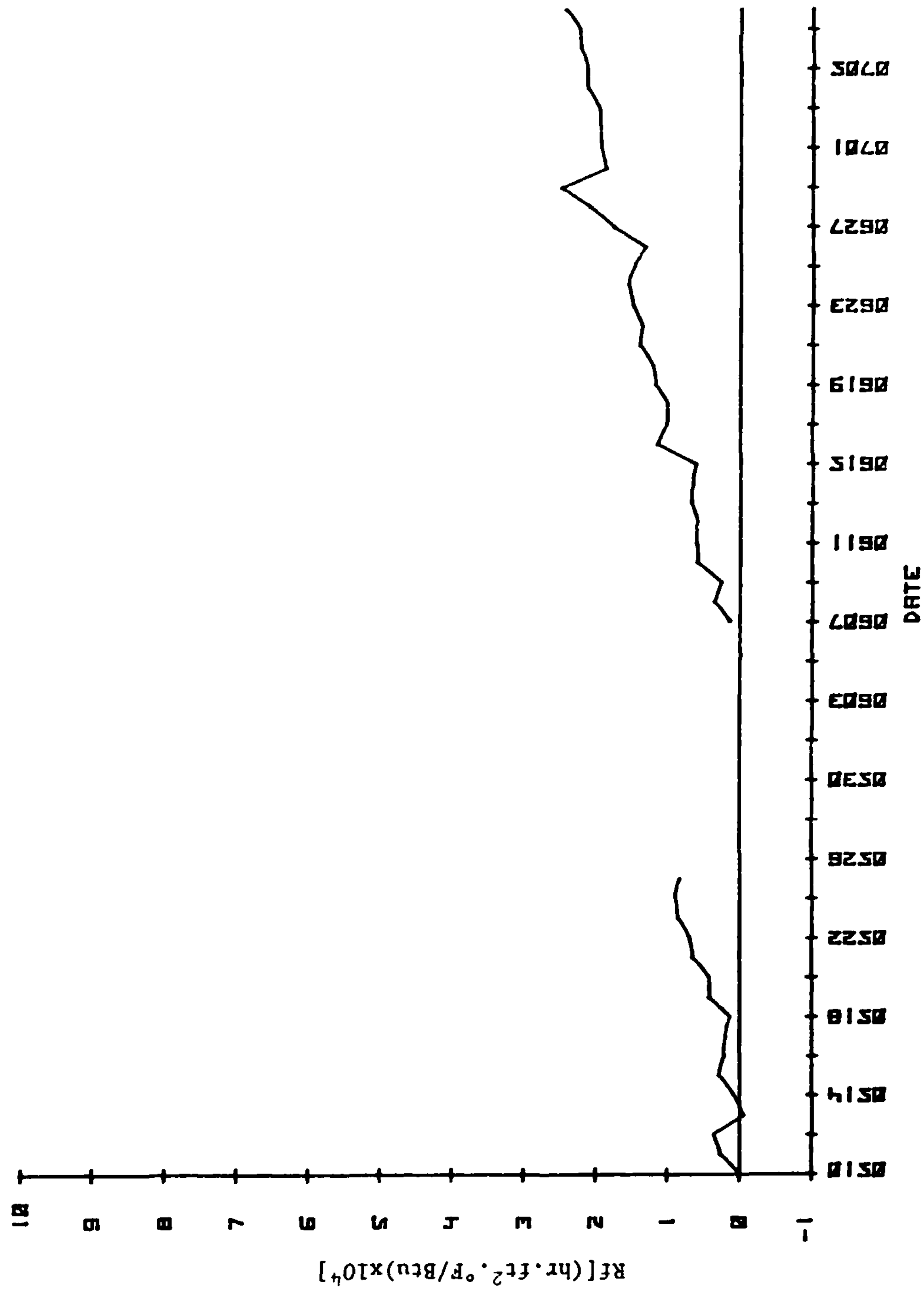

FIGURE 27. FOULING RESISTANCE DATA IN THE ALUMINUM RECIRCULATING SPONGE-RUBBER BALL CLEANING SYSTEM

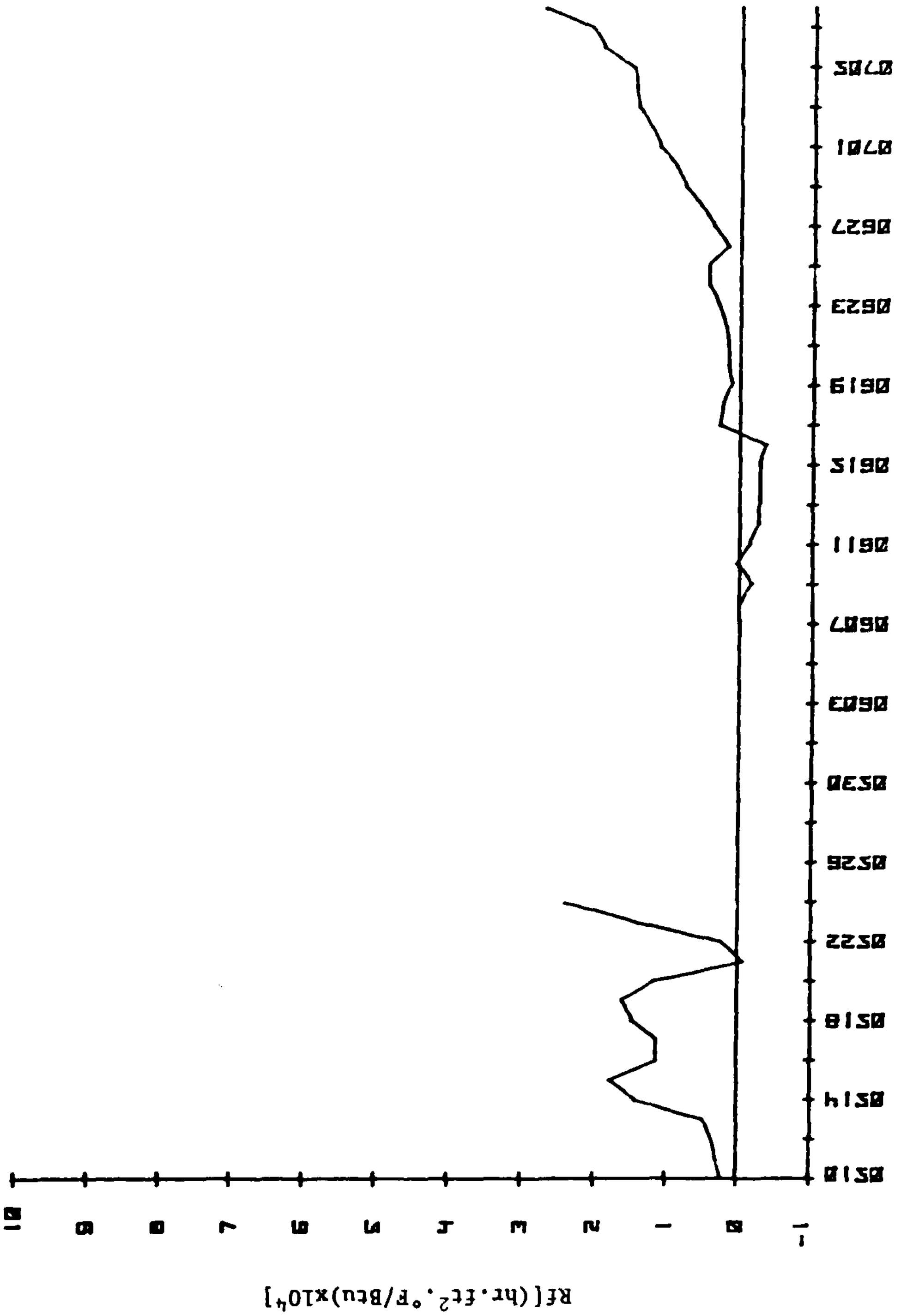

FIGURE 28. FOULING RESISTANCE VERSUS DATE IN THE TITANIUM RECIRCULATING SPONGE RUBBER BALL CLEANING SYSTEM

The tendency toward a gradual increase was similar to that seen with flow-driven brushes.

The titanium pipe, on the other hand, experienced what appeared to be exponential fouling development. After a lag of 10 to 12 days, explosive increases in Rf occurred. This result was quite different from that with flow-driven brushes and represented the first clear instance of enhanced heat transfer capability followed by a sigmoidal increase in Rf as predicted by Characklis[15] and reported by Nimmons[71] and Springer.[4] It is believed that enhancement results from an increase in microroughness within the stagnant sublayer thus increasing surface areas available for convective heat transfer. As long as these roughness elements and the biofilm thickness is less than the viscous sublayer, changes in convective transfer do not affect frictional resistance. When the roughness exceeds the viscous sublayer, increases in frictional resistance occur that are reflected in a diminished heat transfer capability.

Two major problems occurred with the ANL test system which affected system performance and resulted in oscillations in Rf plots for each pipe material. The first of these involved the destruction of test balls during ball release. As soon as rotation from the catch to release position commenced, a suction holding the ball in the catcher was released. The loose ball would become trapped between the ball catcher and the catcher housing. This destroyed the ball and jammed the catcher. This problem was eliminated by installing a pedestal in the catcher that compressed the ball, holding it in the catcher when suction was released. No further problems with ball destruction occurred.

The second and major problem encountered was a tendency for the catcher to "hang open" in the release position. This resulted from an inadequate pressure differential between the seawater header and HTM. Several modifications were attempted but none prevented reoccurrences of the problem. Use of this system was discontinued in later tests.

Controls

Controls, Cleaned Daily. Control results with both systems (Figure 29 for aluminum and Figure 30 for Ti) cleaned daily indicate Rf remained below 1.0×10^{-4} ft^2-hr-°F/Btu for 60-day test period. Toward the end of the experiment, there was a tendency for the Rf to increase. Intensive manual

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[4]ibid.

[15]ibid.

[71]Nimmons, M. J., 1979, "Heat Transfer Effects in Turbulent Flow Due to Biofilm Development," M. S. Thesis, Rice University, Houston, Texas.

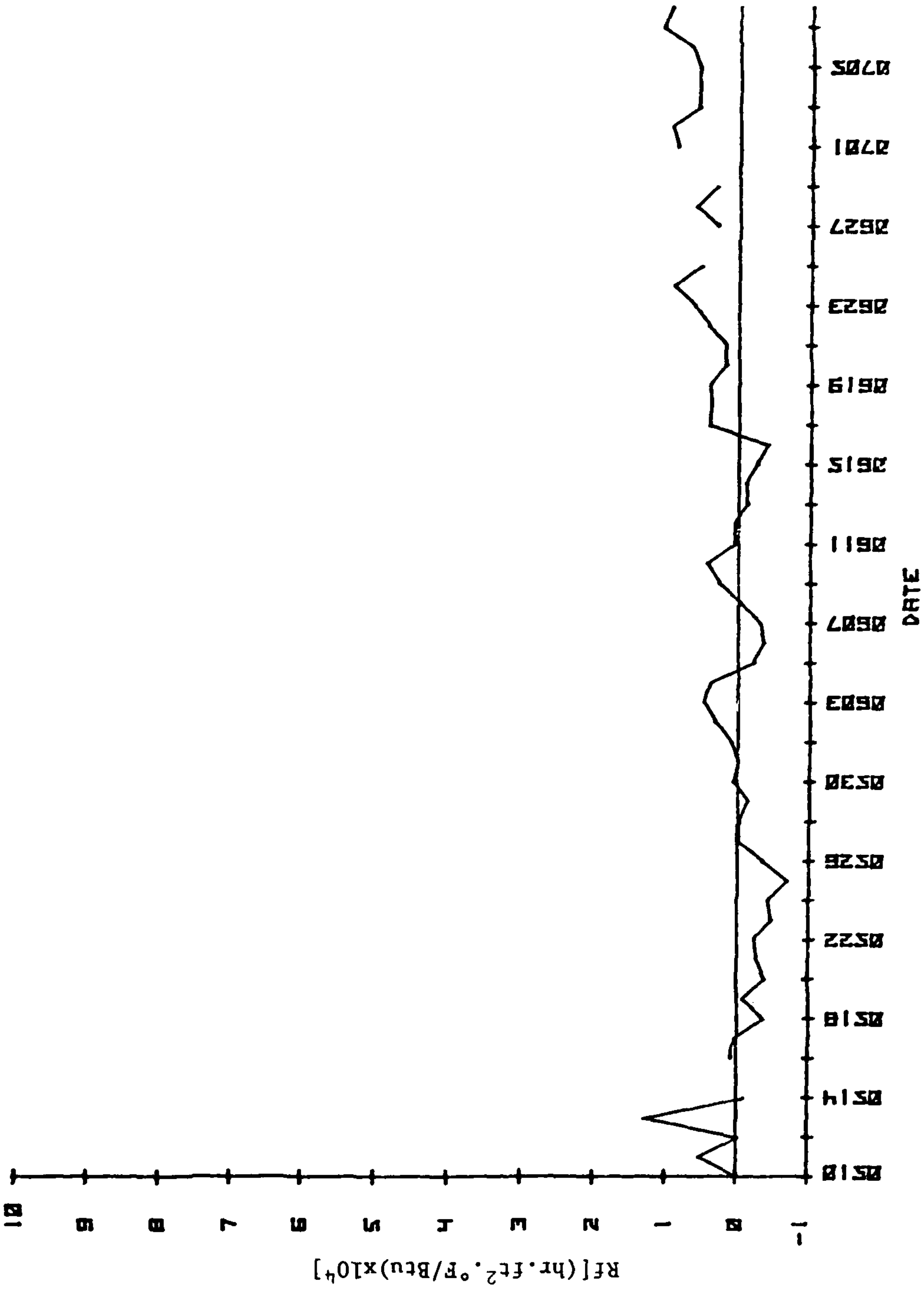

FIGURE 29. FOULING RESISTANCE VERSUS DATE ALUMINUM CONTROL, CLEANED DAILY

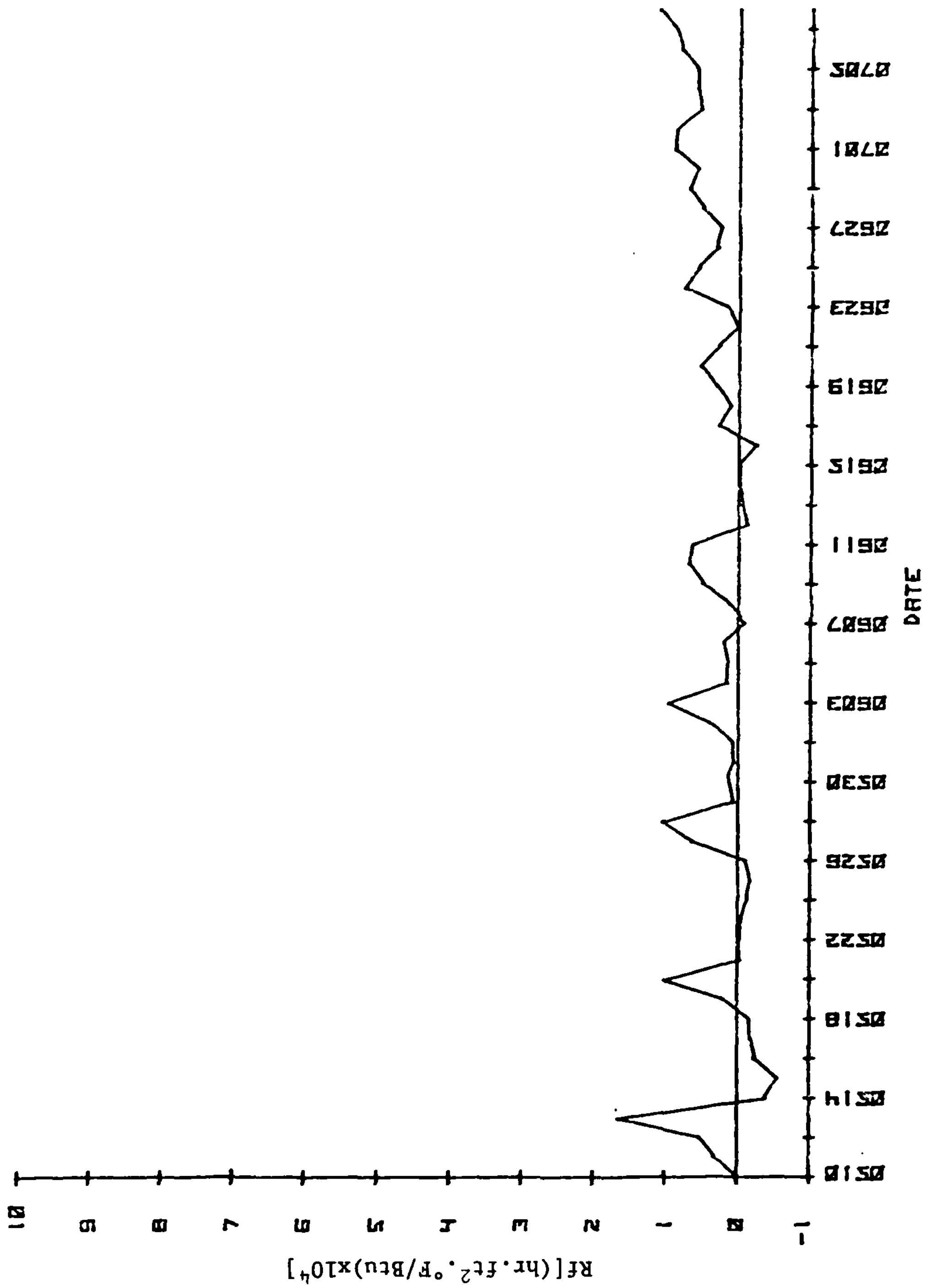

FIGURE 30. FOULING RESISTANCE VERSUS DATE, TITANIUM CONTROL, CLEANED DAILY

brushing could not return Rf to initial values. Also evident in the plots are oscillations (i.e., sharp increases in Rf) due to weekends over which manual brushing was not performed.

Controls, Free Fouling. Results shown in Figure 31 for aluminum and Figure 32 for titanium indicated that titanium fouled to a greater degree than aluminum per unit time. In addition, the titanium pipe could be cleaned to the initial Rf value following a growth cycle. This could not be done in aluminum pipe. This indicated the presence of a thermal insulating layer in aluminum resistant to manual cleaning.

Comment

During this experiment, the long time required to reach an Rf of 5.0×10^{-4} ft^2-hr-°F/Btu became evident. With the change in cleaning requirement from 5.0 to 3.0×10^{-4} ft^2-hr-°F/Btu, the opportunity to decrease the time required per test was presented. Therefore, in all subsequent experiments tests were terminated when Rf exceeded 3.0×10^{-4} ft^2-hr-°F/Btu.

RESULTS OF 1979-1980 EXPERIMENT

Flow-Driven Brushes

Nine tests were completed using flow-driven brushes for cleaning. Four of these tests (Tests 1 through 4) were in aluminum pipe and five (Tests 5 through 9) were in titanium. Parameters for each of these tests are presented in Table 3 with results summarized in Figure 33 for aluminum and Figure 34 for titanium pipe. In addition, detailed monthly plots of Rf are attached as Appendix C for aluminum and Appendix D for titanium.

TABLE 3

TEST PARAMETERS USING FLOW-DRIVEN BRUSHES AS A CLEANING SYSTEM

Test No.	Figure No.*	Duration (Days)	Brush (Size-In.)	Tube** Condition	Cycle (Hrs.)	Chlorine (ppm/15 Min. Daily)
1	33	35	1.05	C	4	0.0
2	33	48	1.05	F	4	1.0
3	33	63	1.05	C	4	1.0
4	33	47	1.15	C	4	0.0
5	34	36	1.05	C	4	0.0
6	34	75	1.05	F	6	0.0
7	34	31	1.05	F	8	0.0
8	34	39	1.05	F	4	0.5
9	34	12	1.15	C	4	0.0

*See appropriate figure for results achieved using the stated test parameters.
**Tube

C = Chemically cleaned tube usually with a Rf < 1.0×10^{-4} ft^2-hr-°F/Btu.
F = Fouled tube whose Rf > 1.0×10^{-4} ft^2-hr-°F/Btu.

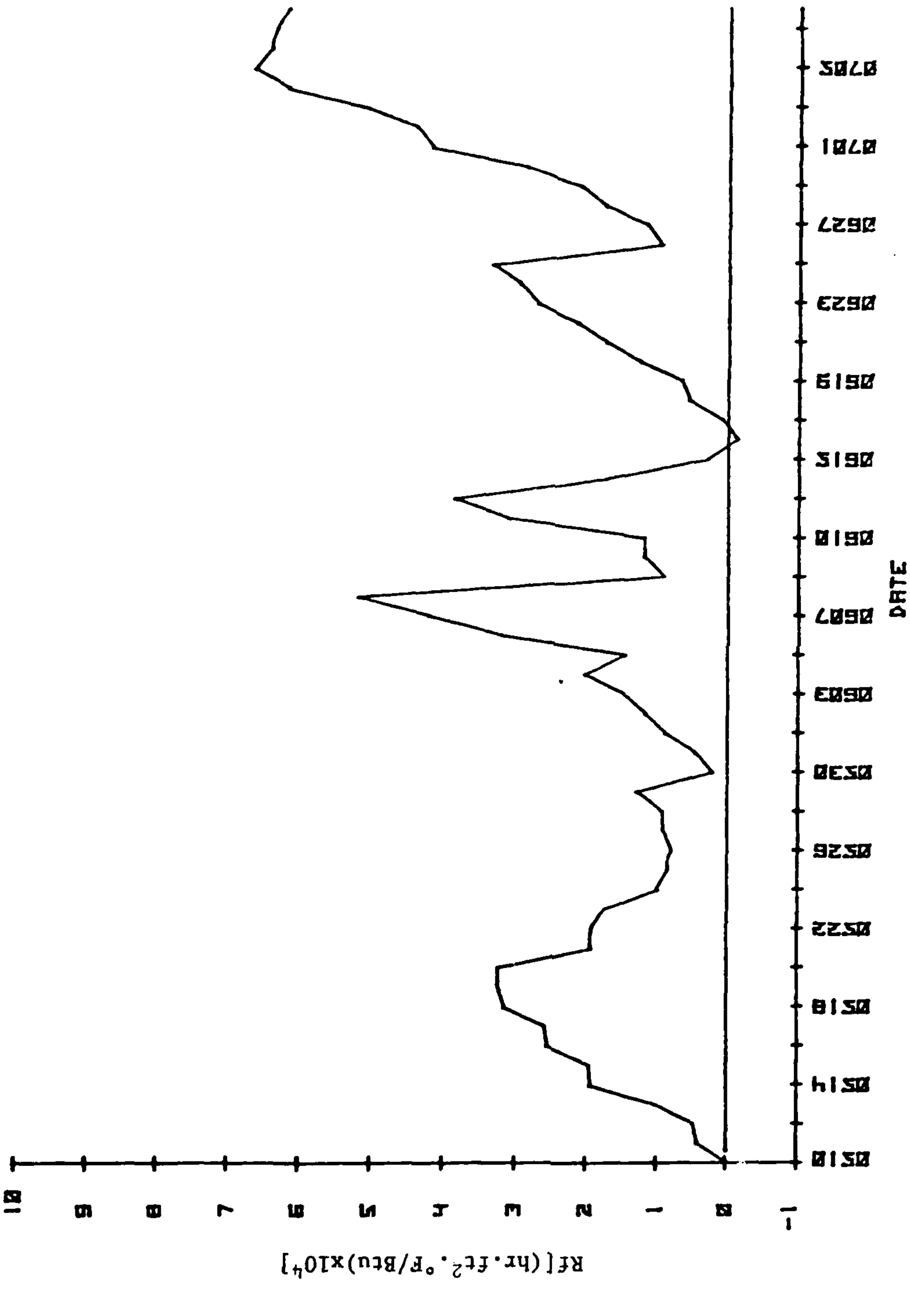

FIGURE 31. FOULING RESISTANCE VERSUS DATE, ALUMINUM FREE FOULING CONTROL

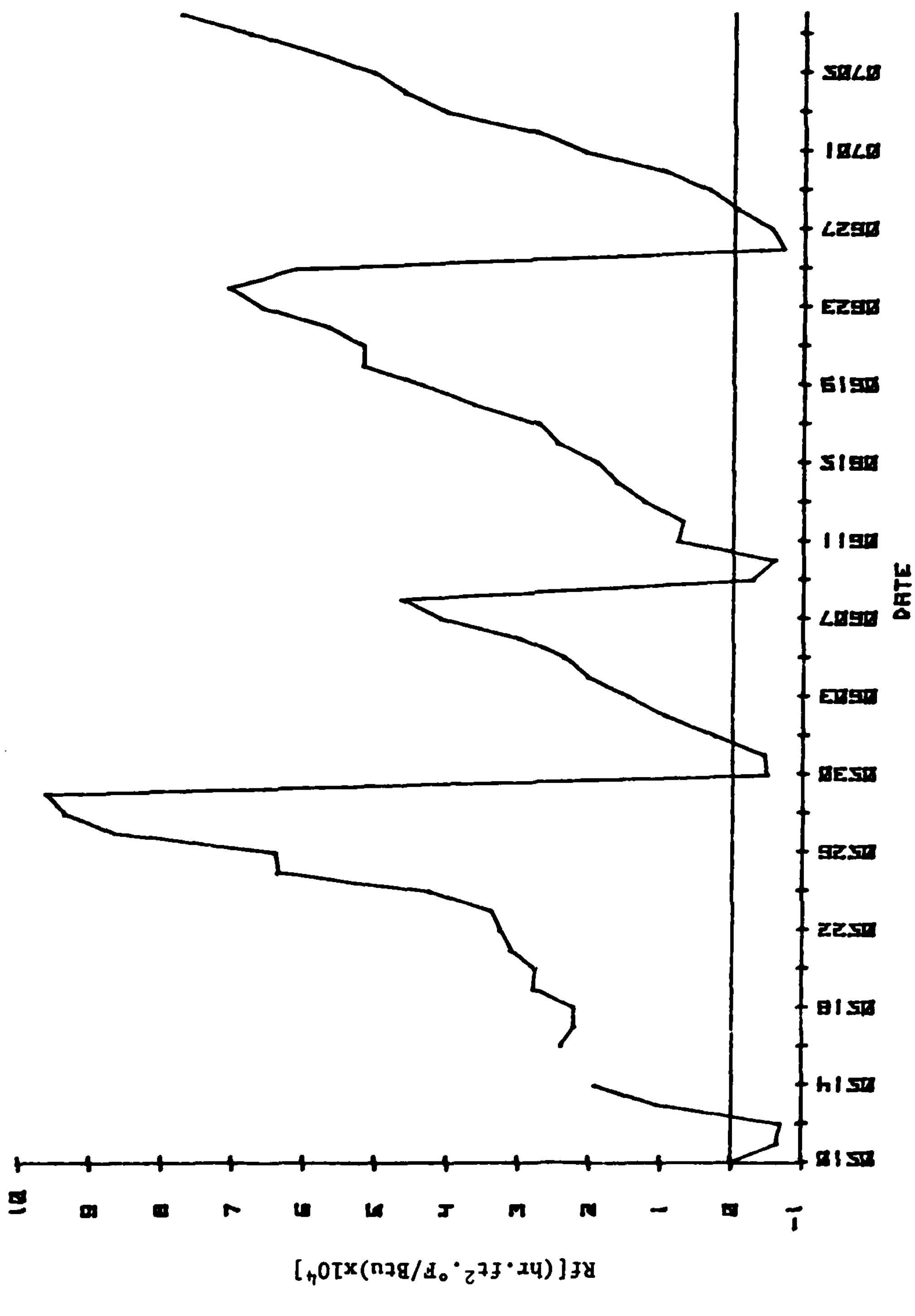

FIGURE 32. FOULING RESISTANCE VERSUS DATE - TITANIUM FREE FOULING CONTROL

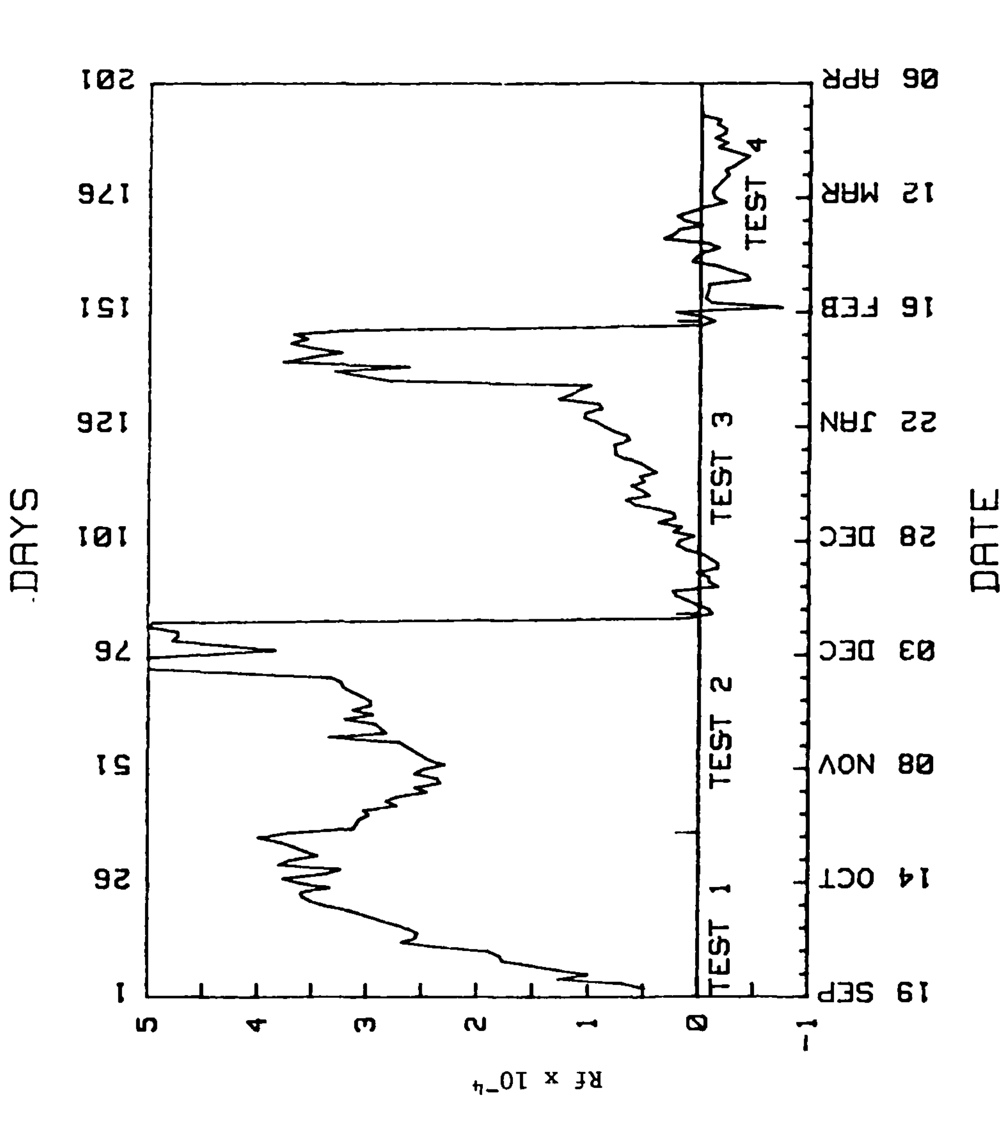

FIGURE 33. FOULING RESISTANCE VERSUS DATE, FLOW-DRIVEN BRUSH IN ALUMINUM PIPE

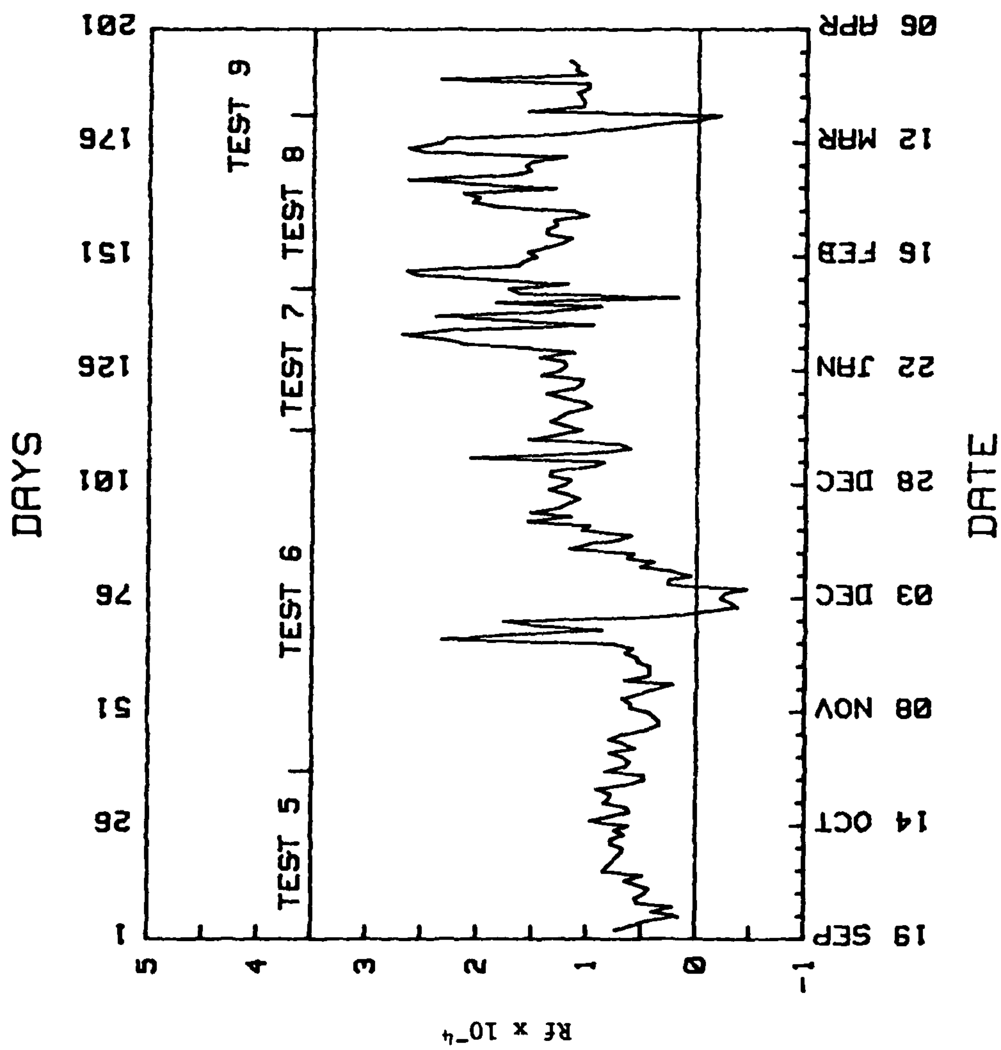

FIGURE 34. FOULING RESISTANCE VERSUS DATE, FLOW-DRIVEN BRUSH IN TITANIUM PIPE

Test 1. This initial test used a 28 mm diameter brush in a clean pipe operating on a 4-hour cleaning cycle. Under these conditions, the Rf rapidly increased with the target level exceeded within 5 days.

Test 2. When chlorine (1 ppm total residual/15 minutes daily) was added to the fouled pipe of Test 1, there was a transient decrease in Rf followed by a sharp increase.

Test 3. Since Rf continued to increase under Test 2 conditions, the pipe was recleaned, recalibrated, and restarted using the 28-mm brush, a clean tube, and chlorination. Though increases in Rf were significantly delayed, they ultimately reached similar levels of Rf as when chlorine was not used. The low level of chlorine used (0.01 ppm average daily residual), therefore, was not effective.

Test 4. The single test of the 29-mm diameter brush in a clean tube operating on a 4-hour cycle provided the best results achieved to date in aluminum pipe. Under these test conditions, Rf was kept below target levels for 47 days.

It was apparent that for the conditions tested in the aluminum pipe, the 28-mm brush could not keep Rf at target levels, while the larger (29 mm) brush performed well. Further testing is required to determine how long Rf would stay below target levels using this larger brush.

Test 5. The initial test in titanium used the 28-mm brush in a clean pipe operating on a 4-hour cycle. Excellent results were obtained, with Rf remaining well below target levels for 36 days.

Test 6. On day 37, the cleaning cycle interval was switched from 4 to 6 hours. Rf, although erratic, remained at or near the target level of 1.0×10^{-4} ft^2-hr-°F/Btu.

Test 7. Since Rf had not greatly exceeded the target level, the cleaning cycle interval was increased from 6 to 8 hours. Results were much more erratic and Rf averaged 1.5×10^{-4} ft^2-hr-°F/Btu.

Test 8. In an effort to reduce Rf to target level, the cycle interval was reduced to 4 hours and chlorination was begun. These test conditions had no apparent effect on reducing Rf.

Test 9. Following Test 8, the pipe was chemically cleaned, recalibrated, and run on a 4-hour cycle with the 29 mm diameter brush. This brush performed poorly in contrast with results it achieved in aluminum pipe.

It was evident that, for conditions tested, target levels of Rf could be achieved in titanium pipe using the 28-mm brush operating on a 4, 6, or 8-hour cycle. Further study is required, however, concerning the response of titanium to (1) cleaning effectiveness and (2) seasonal rates of fouling. It should be

noted that most of the tests were conducted during colder months (September through January). During this period, titanium pipe consistently outperformed aluminum in heat transfer. Results during those transition months in which both air and water temperatures were warming indicated that aluminum transferred heat better than titanium.

Much of the biofilm accumulation problem results from the cleaning process. White[69] has found that cleaning aluminum pipe with flow-driven brushes is selective for specific bacterial components within the fouling community and is responsible for an increase in exopolymer production. The exopolymer resists stresses from the environment while a gradual accumulation of the selected bacteria occurs. This would be reflected as a diminished heat transfer capability. Cleaned titanium pipe, in contrast, yields a diverse biofilm rich in filamentous bacteria and blue-green algae but with a reduced exopolymer content. Thus the increased fouling rate seen with titanium is due to a general increase in all classes of microorganisms and not selection for a specific bacterial class.

Recirculating Sponge Rubber Balls

Thirteen tests were completed using recirculating sponge rubber balls for cleaning. Six were completed in aluminum (Tests 1 through 6) and seven were completed in titanium pipe (Tests 7 through 13). Test descriptions appear in Table 4 with results plotted in Figure 35 for the aluminum tests and Figure 36

TABLE 4

TEST PARAMETERS USING RECIRCULATING SPONGE RUBBER BALLS AS A CLEANING SYSTEM

Test No.	Figure No.*	Duration (Days)	Cycle (Min.)	Tube** Condition	Chlorine (ppm/15 Min. Daily)
1	35	43	15	C	0.0
2	35	40	30	F	0.0
3	35	28	30	F	1.0
4	35	35	15	F	1.0
5	35	33	15	C	1.0
6	35	10	15	F	2.0
7	36	41	15	C	0.0
8	36	36	30	F	0.0
9	36	33	60	F	0.0
10	36	50	60	F	0.5
11	36	10	120	F	0.5
12	36	6	60	F	0.5
13	36	10	60	F	1.0

*See appropriate figure for test results achieved using stated test parameters.
**Tube

C = Chemically cleaned tube usually with a Rf < 1.0 X 10^{-4} ft^2-hr-°F/Btu.

F = Fouled tube whose Rf > 1.0 X 10^{-4} ft^2-hr-°F/Btu.

[69]ibid

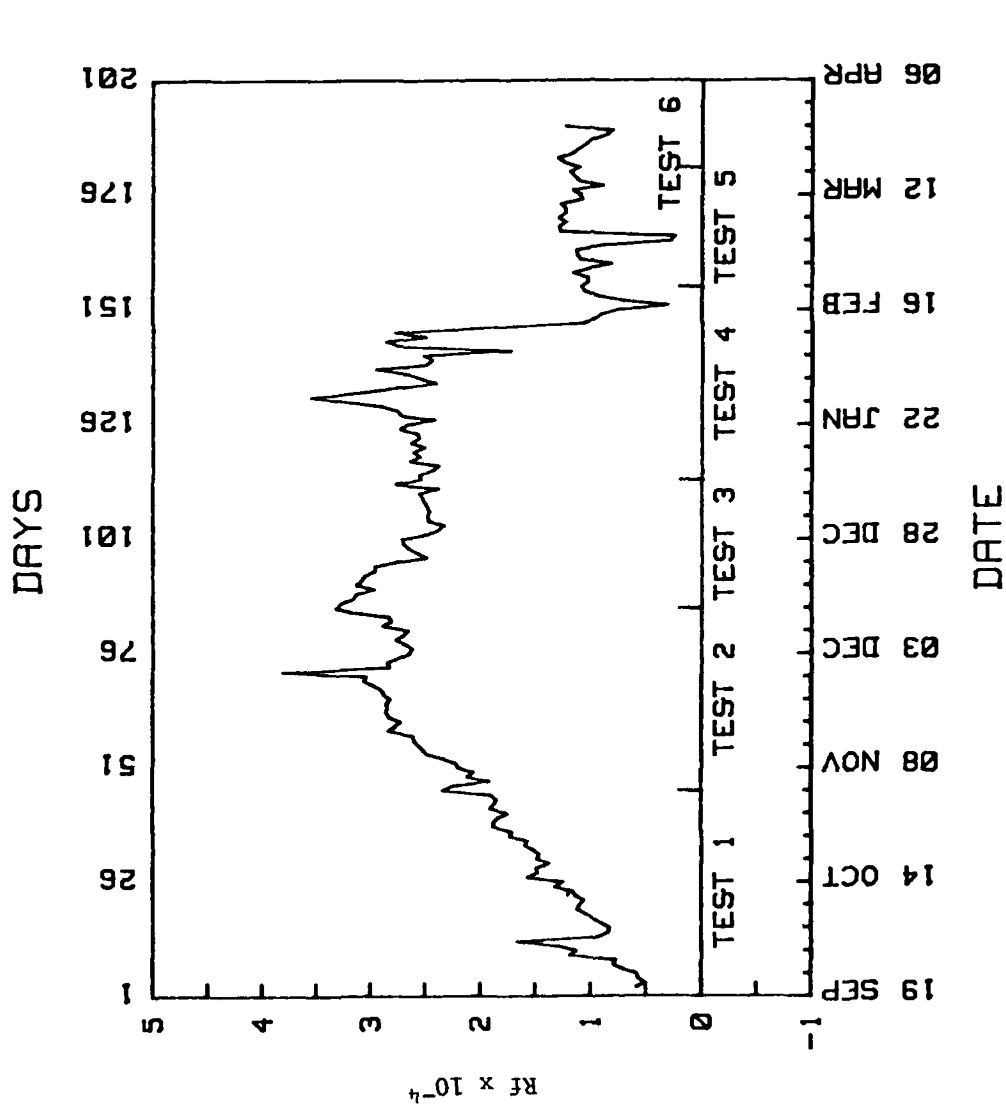

FIGURE 35. FOULING RESISTANCE VERSUS DATE, RECIRCULATING SPONGE RUBBER BALLS IN ALUMINUM PIPE

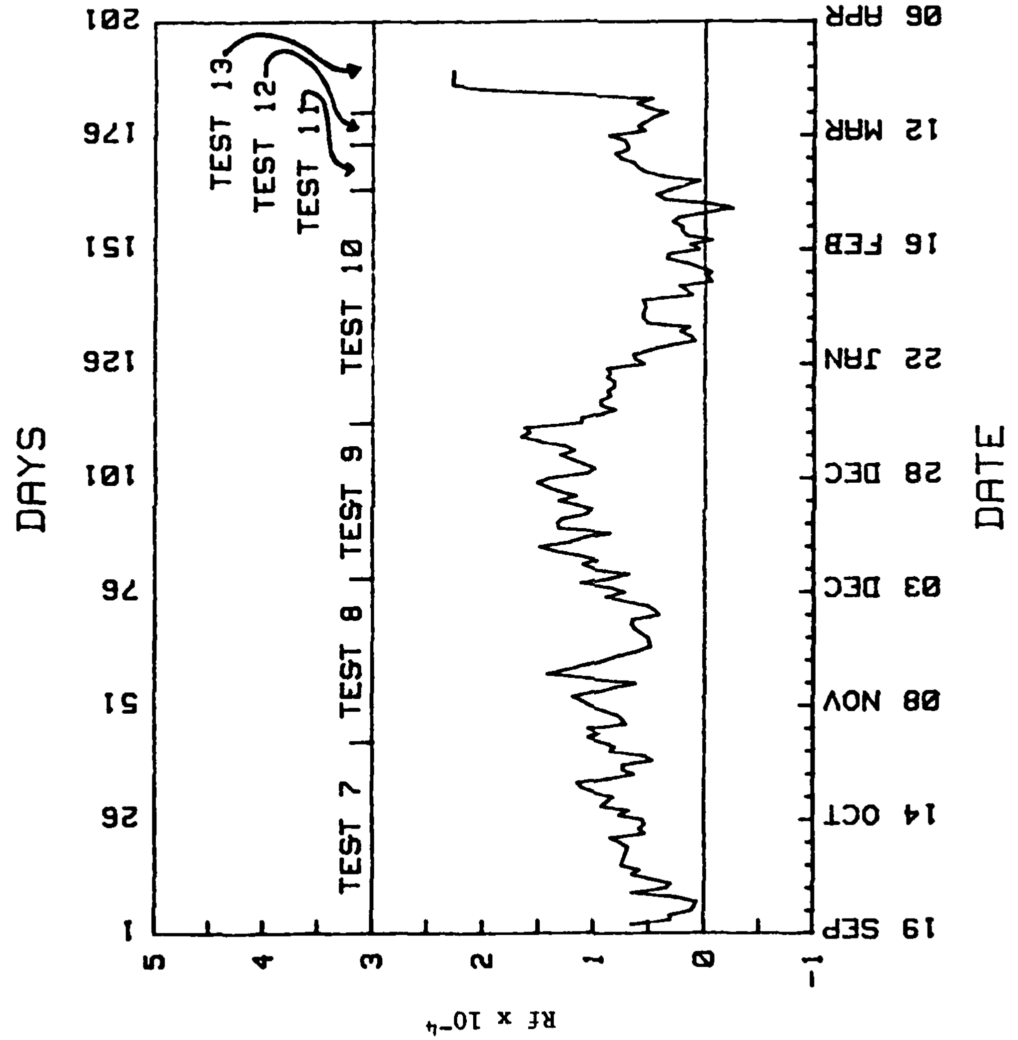

FIGURE 36. FOULING RESISTANCE VERSUS DATE, RECIRCULATING SPONGE RUBBER BALLS IN TITANIUM PIPE

for the titanium tests. Detailed monthly plots of the Rf are attached as Appendix E for aluminum and Appendix F for titanium.

Test 1. The initial test used a clean tube on a 15-minute cleaning interval. At these conditions, the Rf steadily increased with the target level being exceeded within 20 days.

Test 2. After 43 days, the cleaning interval was increased from 15 to 30 minutes. This interval was an attempt to increase the fouling rates so that ongoing biological sampling could be performed. Note that the biological tests had a higher target Rf (Rf = 5.0×10^{-4} ft^2-hr-°F/Btu) than the cleaning tests. From the results, it was apparent that doubling the cycle interval had no effect on the rate of fouling.

Test 3. When chlorine (1.0 ppm total chlorine residual for 15 minutes daily) was added to the fouled tube reset to a 15-minute cycle from the 30-minute cycle used in Test 2; the Rf stabilized but at a value significantly higher than the target level of 1.0×10^{-4} ft^2-hr-°F/Btu.

Test 4. In an attempt to reduce the Rf in Test 3 to tolerable levels, the cleaning interval was reduced from 30 to 15 minutes. This reduction between cleaning cycle intervals had no effect on the Rf, however.

Test 5. Since the addition of chlorine to the fouled tube operating on either 15- or 30-minute cycles did not reduce the Rf to target levels, the pipe was recleaned, recalibrated, and run on a 15-minute cycle with chlorination. Results indicated that the Rf would stabilize under these conditions at or near the target level.

Test 6. Toward the end of field tests, the chlorine concentration was doubled from 1 ppm to 2 ppm total chlorine residual for 15 minutes daily. Doubling the chlorine concentration had no effect on the stabilized Rf.

It was apparent from our tests in aluminum pipe that only one test combination kept the Rf at target levels: a 15-minute cleaning cycle in a clean pipe subjected to chlorination. However, short-term problems which prevented ball movement significantly affected Rf values. Thus, questions arise concerning the effectiveness of chlorine once a pipe has fouled which should be the subject of future studies.

Test 7. This initial test of titanium pipe used a clean tube operating on a 15-minute cycle. In these conditions, Rf stabilized around 0.6×10^{-4} ft^2-hr-°F/Btu which was well below the target levels.

Test 8. This test extended the cleaning cycle interval from 15 to 30 minutes. Doubling the interval did not affect stabilized Rf which remained near 0.6×10^{-4} ft^2-hr-°F/Btu.

Test 9. Test 9 sought to further increase the interval between cleaning cycles. Increasing the interval from 30 to 60 minutes increased the Rf to approximately 1.5×10^{-4} ft^2-hr-°F/Btu and stabilized the Rf at that value.

Test 10. In an attempt to reduce the Rf back to the target level, chlorine was added to the fouled tubes operating on the 60-minute cycle. Chlorine addition reduced the Rf from 1.5 to 0.5×10^{-4} ft^2-hr-°F/Btu. The Rf appeared to stabilize but system problems, such as prevention of ball movement, seriously affected the Rf values.

Test 11. This test doubled the cycle interval from 60 to 120 minutes in the fouled pipe subject to chlorination. Again Rf increased but stabilized at a value (0.6×10^{-4} ft^2-hr-°F/Btu) significantly below target levels.

Test 12. In an effort to reduce Rf from 0.6×10^{-4} ft^2-hr-°F/Btu to a lower value, the cycle interval was reduced to 60 minutes while continuing chlorination. No effect could be seen on the Rf.

Test 13. The final test doubled the chlorine concentration from 0.5 to 1.0 ppm total residual for 15 minutes daily. The doubling of chlorine appeared to have little effect on the Rf. However, a major power failure occurred 27 March that prematurely ended data collection.

In summary, a number of options resulted in acceptable Rf values in titanium pipe. The sponge rubber ball alone operating on a 15, 30, or 60-minute cycle performed well. When chlorine was added at a dosage of 0.5 ppm total residual for 15 minutes daily, the cycle interval could be extended to 120 minutes. Throughout these tests, the mechanical systems for ball recirculation performed well. This allowed evaluation of cleaning effectiveness of the ball but not an evaluation of the reliability of mechanical control of the ball's movement.

At least once during field tests of recirculating sponge rubber balls in combination with chlorination, a brown residue formed on the waterside surfaces of both the aluminum and titanium pipes. This phenomenon has been previously reported.[48 72] The residue consisted of silicone dioxide, an inorganic carbonate, and manganese.[73] Although the residue would reduce or prevent fouling,

[48]ibid.

[72]Adamson, W. L., 1976, "Marine fouling of Titanium Heat Exchangers," David W. Taylor Naval Ships Research and Development Center, Annapolis, MD, Report No. PAS-75-29.

[73]Mangum, D. and McIlhenny, W., 1975. Control of marine fouling in intake systems--a comparison of ozone and chlorine. In Aquatic Applications of Ozone, Edited by Blogoslawski, W. and Rice, R., pp. 138-153. Internatl. Ozone Inst.

its own thickness would severely reduce heat transfer. Although the residue was easily removed by brushing between experimental runs, it is normally removed by the action of flowing seawater once chlorination ceases.[72]

During Test 1 of the recirculating sponge rubber balls, pipe samples were removed and sent to Dr. D. C. White for analysis. White[69] concluded that cleaning of the aluminum pipe with the recirculating ball system under Test 1 conditions resulted in a progressive increase of filamentous microbes with exposure. Titanium showed similar results with microbial filaments shorter and less pervasive than those in aluminum pipe.

Chlorination

Four tests were completed using chlorination alone as a biofouling countermeasure. These tests are described in Table 5 with results presented in Figures 37 and 38 for aluminum and titanium pipe, respectively. Concurrent testing with mechanical systems prevented a wider range of tests with chlorine alone. Detailed monthly plots of Rf are attached as Appendix G for aluminum and Appendix H for titanium.

TABLE 5

TEST PARAMETERS USING CHLORINATION AS A CLEANING SYSTEM

Test No.	Figure No.*	Duration (Days)	Tube** Condition	Chlorine Dosage (ppm/15 Min. Daily)
1	37	179	C	1.0
2	37	15	F	2.0
3	38	179	C	0.5
4	38	15	F	1.0

*See appropriate figure for results achieved with test parameters stated.
**Tube

C = Chemically cleaned tube usually with a Rf < 1.0 X 10^{-4} ft^2-hr-°F/Btu.

F = Fouled tube whose Rf > 1.0 X 10^{-4} ft^2-hr-°F/Btu.

[69]ibid.

[72]ibid.

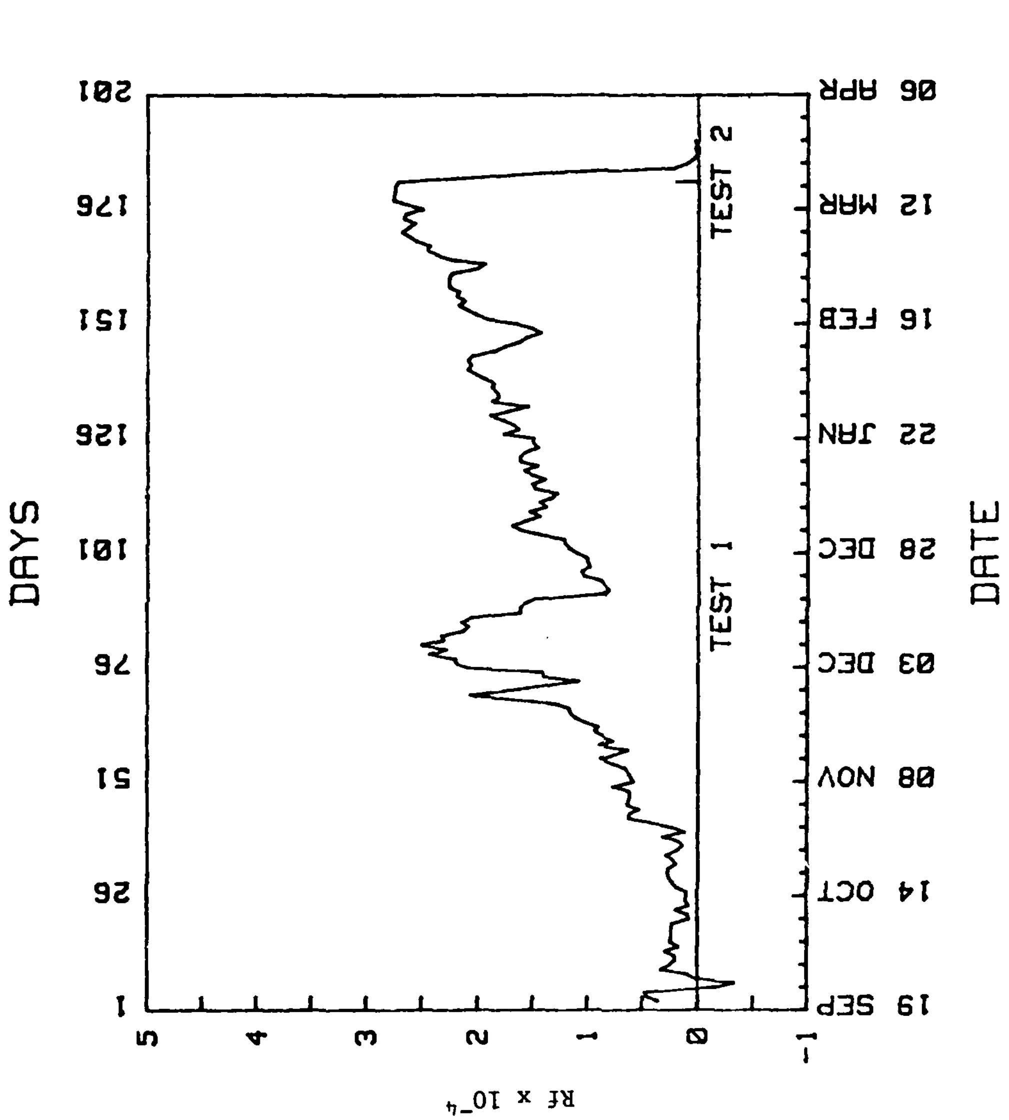

FIGURE 37. FOULING RESISTANCE VERSUS DATE, CHLORINATION TESTS IN ALUMINUM PIPE

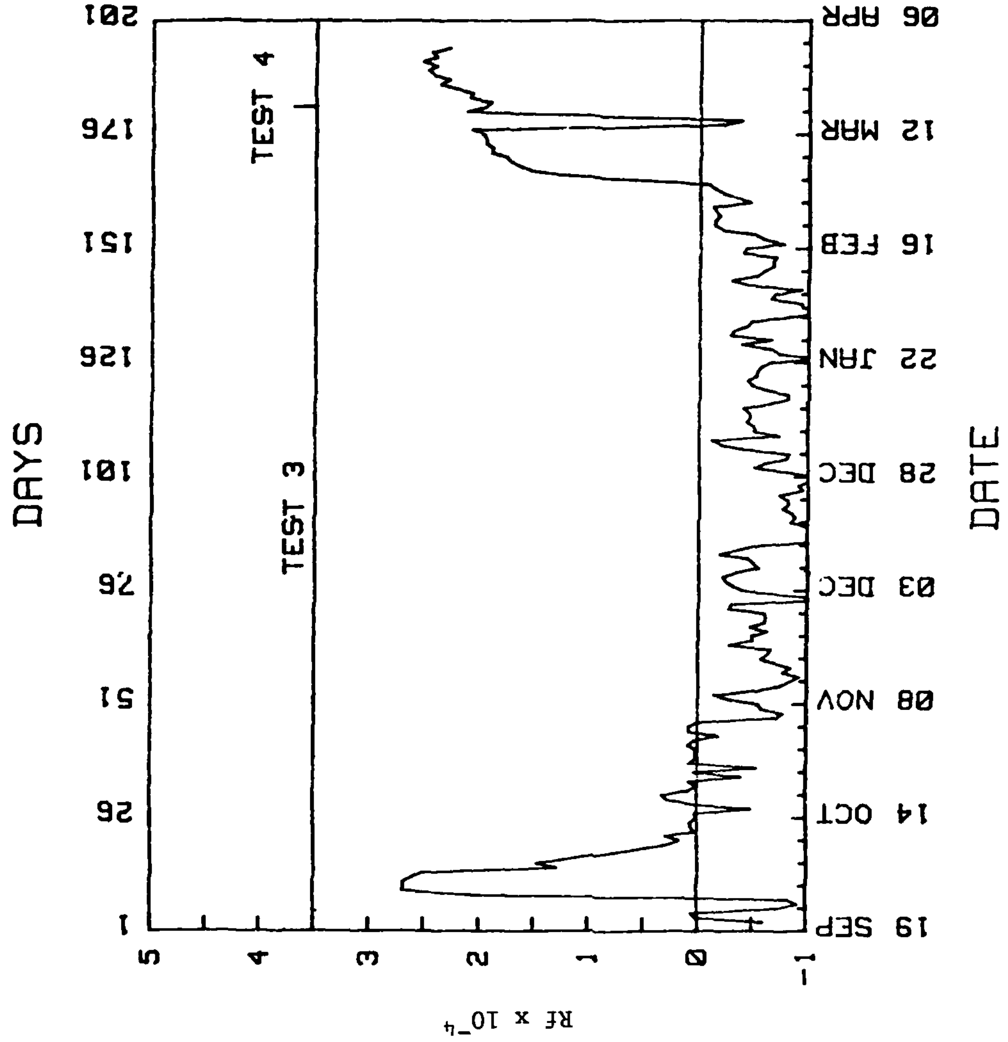

FIGURE 38. FOULING RESISTANCE VERSUS DATE, CHLORINATION TESTS IN TITANIUM PIPE

Test 1. The initial chlorination test of aluminum pipe used 1.0 ppm total chlorine residual for 15 minutes daily. This level of chlorination resulted in a steadily increasing Rf. At the end of 180 days, Rf approached 2.7×10^{-4} ft^2-hr-°F/Btu.

Test 2. Test 2 doubled the chlorine concentration in an effort to "shock" the pipe and return the Rf to acceptable levels ($<1.0 \times 10^{-4}$ ft^2-hr-°F/Btu). Doubling the chlorine residual reduced the Rf to zero; however, whether this decrease was transient or long-term was not determined due to the termination of field tests.

The results in aluminum thus indicate that the Rf may be returned to acceptable levels with higher chlorine dosages. This assumes an acclimation of the fouling community to the daily chlorination regime. The conclusion is that "shock" chlorination may be useful in returning a pipe to acceptable levels from the fouled state. This could eliminate costly breakdowns and associated cleaning of the heat exchangers.

Test 3. The titanium pipe was subjected to a chlorine dosage of 0.5 ppm total chlorine residual for 15 minutes daily. This pipe remained below target levels for 156 days after which there was a sharp increase in Rf. This increase may be related to an increase in ambient temperature and thus an increase in fouling rate.

Test 4. The final test in titanium involved an increase of the chlorine residual from 0.5 to 1.0 ppm for 15 minutes daily. Doubling the chlorine residual had no effect on Rf.

In summary, a chlorine residual of 0.5 ppm for 15 minutes daily kept the Rf in titanium pipe below target levels for 156 days. Further work should be done to determine a "shock" chlorine residual that would return the fouled pipe to an acceptable Rf.

The results achieved with very low dosages of chlorine alone were startling. Although the high seawater flow rate enhanced the effect of chlorine, the low mean daily average chlorine dose (0.01 ppm total chlorine residual 15 minutes daily) was significantly lower than the effective antifouling dosage of 1 ppm free-residual chlorine for 1 hour every 8 hours reported by Fava.[48] The rapid regrowth experienced in many cases following chlorination is due to a failure to carry oxidation of the biofilm to completion.[36] Remaining biofilm constituents are responsible for the regrowth phenomenon. This is partially borne out by Martin[74] who reported that gelatinous

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[36]ibid.

[48]ibid.

[74]Martin, R. B., 1938. Chlorination of Condenser Cooling Water. Trans. Amer. Soc. Mech. Engrs pp. 475-483.

slime-formers were more susceptible than nongelatinous slime-formers when exposed to chlorine dosages of <0.5 mg/l and contact times ranging from 10 seconds to 60 minutes.

Controls

Controls, Cleaned Daily. Controls performed as expected during the tests. For both the aluminum and titanium tubing cleaned daily (Figures 39 and 40), the Rf remained at or near target levels. During the latter portions of the test program, pipes were allowed to foul to higher levels to test the response of the data-gathering system to the Rf increases. Detailed monthly plots of the Rf in these controls are attached as Appendix I for aluminum and Appendix J for titanium.

Controls, Free Fouling. The free-fouling controls experienced nine fouling cycles for aluminum (Figure 41) and 10.5 for titanium (Figure 42) during the 195 days of field tests. Biological tests utilizing these controls were performed in conjunction with Dr. D. C. White, Florida State University, and have been reported in separate papers.[67 68 69] Results indicate that fouling per unit time is greater in titanium than in aluminum. Conn[39] theorized that the greater fouling rate exhibited by titanium was related to the roughness of waterside surfaces and the protected settlement sites offered by such surfaces. White has shown a greater profusion of filamentous microbes on titanium waterside surfaces than on aluminum ones. Thus, the effect of filamentous microbes on frictional resistance may be the mechanism directly responsible for increases in heat transfer resistance.

Throughout the field experiments, aluminum proved difficult to clean. After manually brushing the free-fouling pipes, a residual film of filamentous organisms remained on or under the aluminum corrosion gel.[69] These protected microbes form the basis for a quick regrowth of the biofilm and high initial "nonbiological resistances" determined in some Wilson plots.

Fouling communities on titanium and aluminum are similar in that both pipes exhibit communities rich in filamentous bacteria. Titanium pipe, however, yields a more diverse fouling population with both blue-green algae and microeukaryotes abundant.[69]

Monthly plots of the Rf for aluminum and titanium are contained in Appendices K and L.

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[39]ibid.

[67]ibid.

[68]ibid.

[69]ibid.

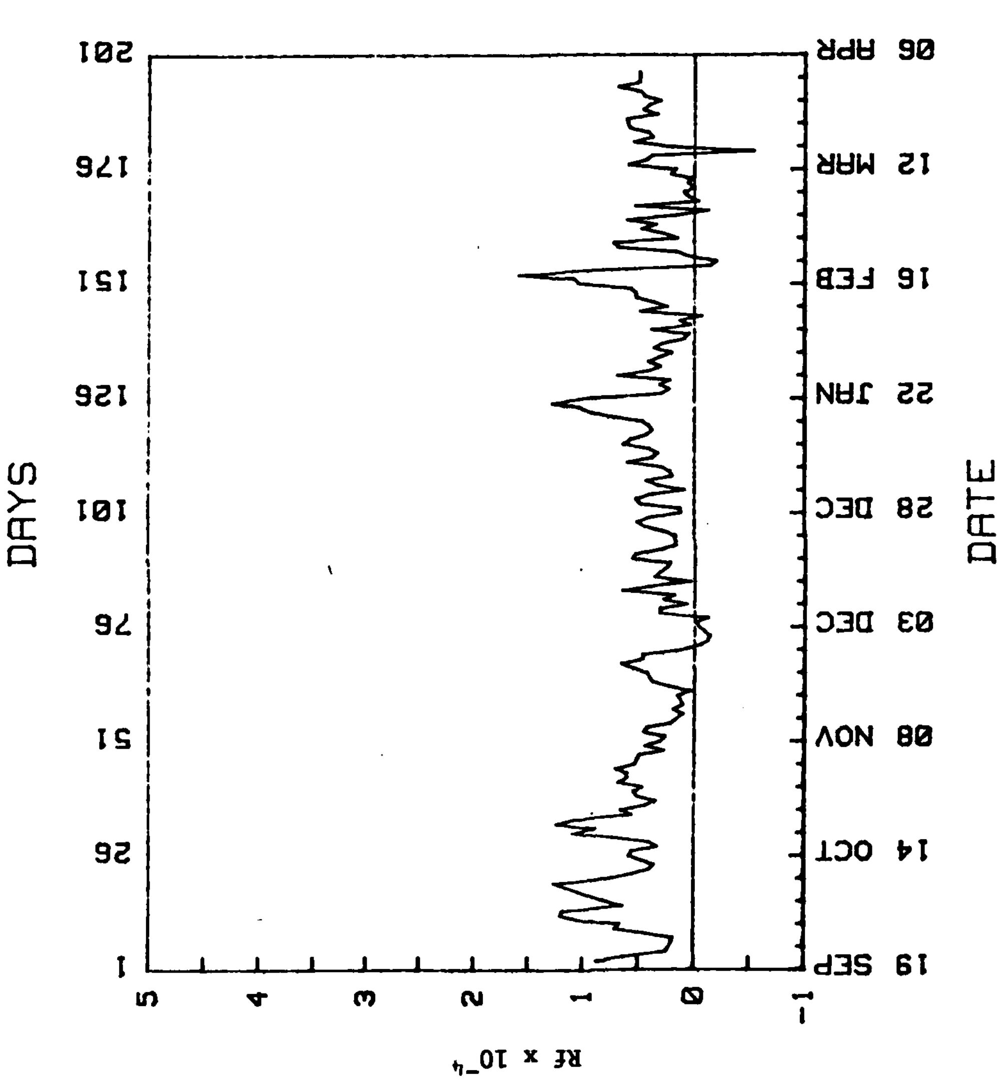


FIGURE 39. FOULING RESISTANCE VERSUS DATE, ALUMINUM CONTROL, CLEANED DAILY

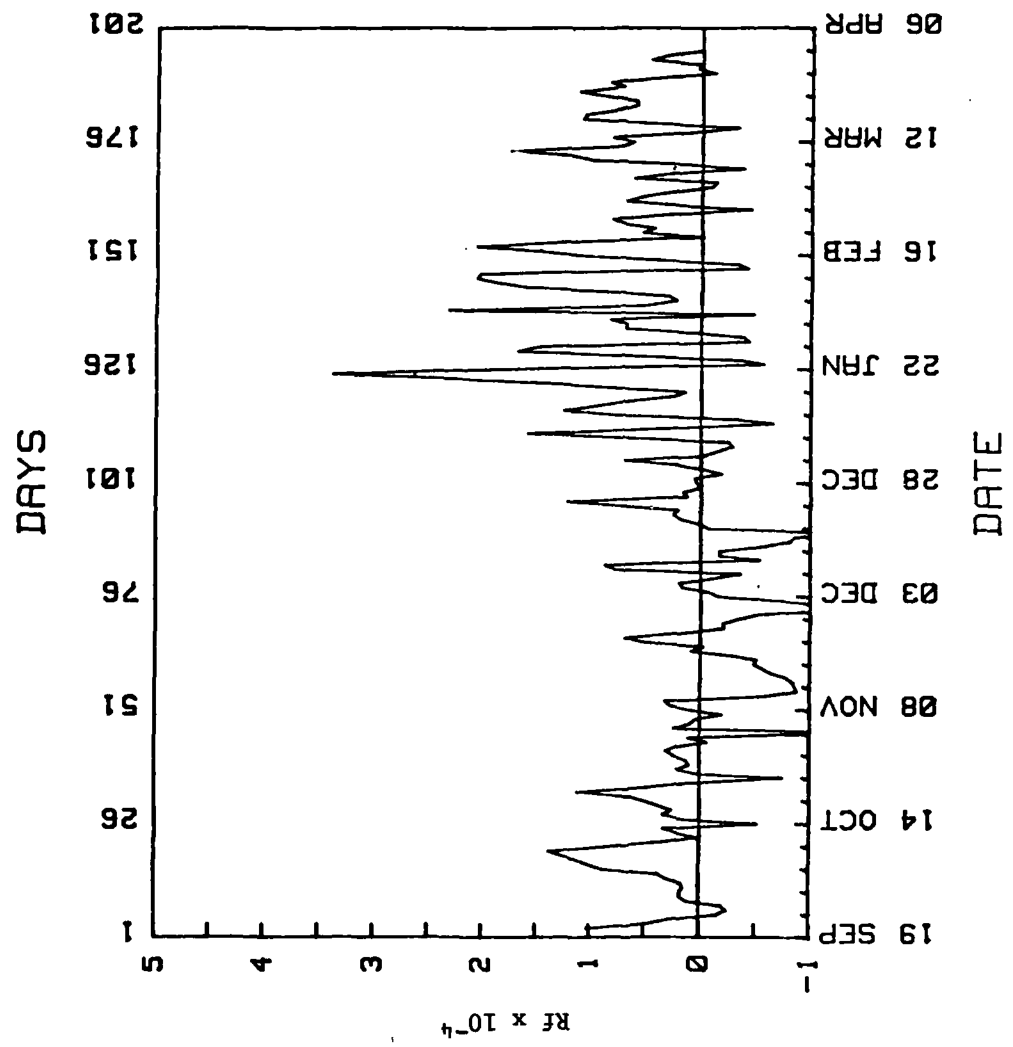


FIGURE 40. FOULING RESISTANCE VERSUS DATE, TITANIUM CONTROL, CLEANED DAILY

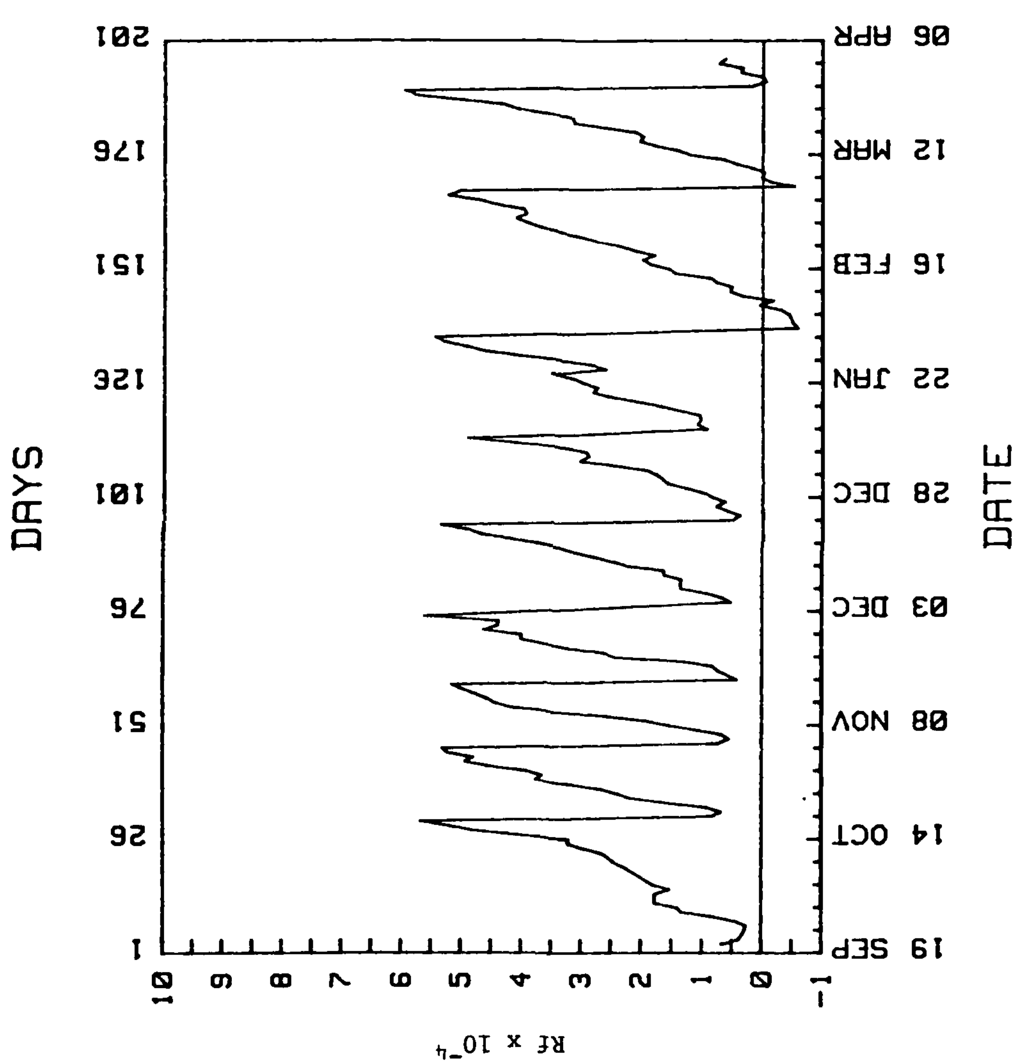


FIGURE 41. FOULING RESISTANCE VERSUS DATE, ALUMINUM FREE FOULING CONTROL

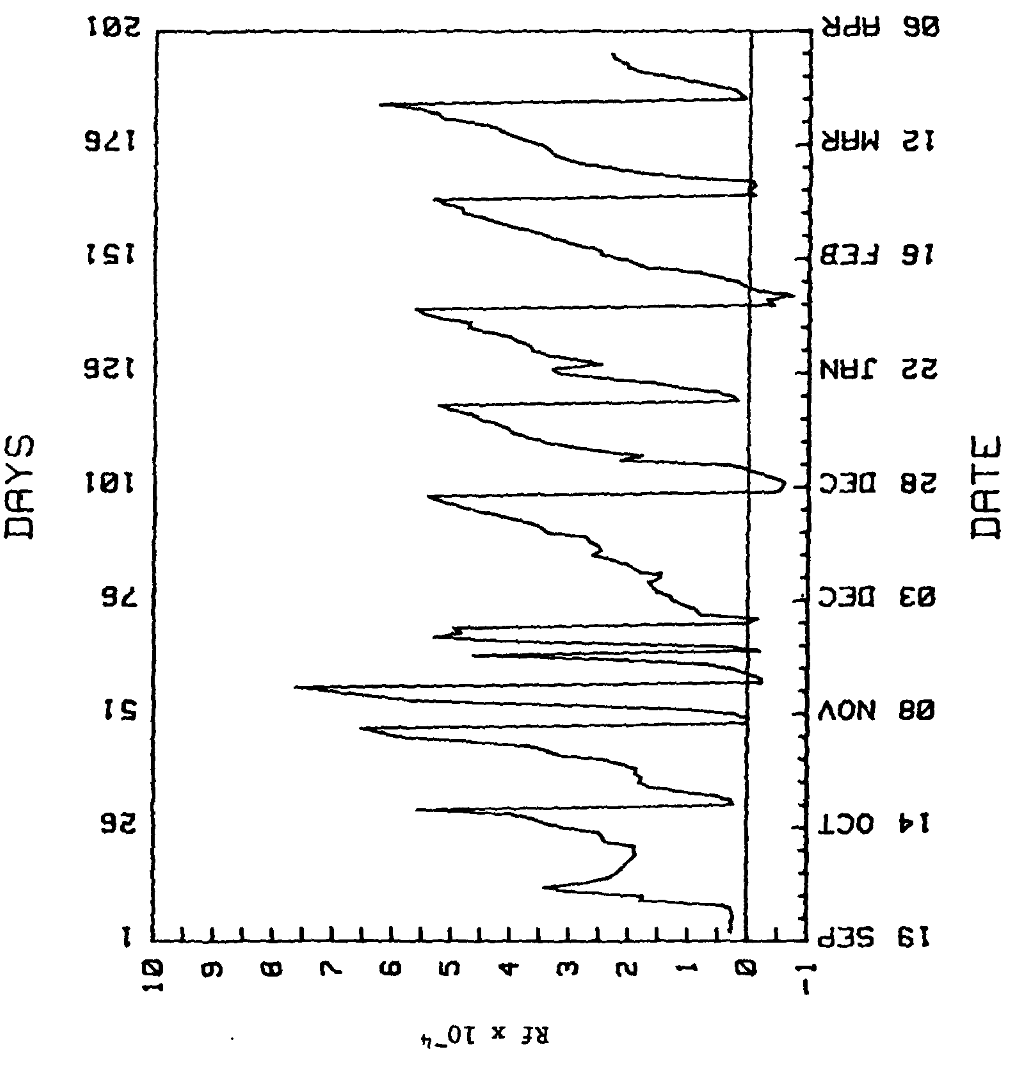


FIGURE 42. FOULING RESISTANCE VERSUS DATE, TITANIUM FREE FOULING CONTROL

Comment

Field testing ended with the scheduled termination of all experiments on 31 March 1980.

CONCLUSIONS

Maintenance of OTEC heat exchangers at high heat transfer efficiencies appears feasible with a variety of cleaning systems. These options are:

a. Aluminum Pipe

(1) Flow-Driven Brushes. Results indicate that a 29-mm diameter experimental brush kept the Rf at target levels while the 28-mm brushes (the commercially recommended brush and the experimental brush) did not. Further study is needed to verify the seasonal effectiveness of the 29-mm brush.

(2) Recirculating Sponge Rubber Balls. Using a variety of recirculation systems, i.e., peristaltic pumps, ANL pressure system, or NCSC mechanical system, the sponge rubber ball alone did not prevent an increase in Rf. However, Rf increases were prevented using this system in conjunction with chlorination. Specifically, a clean pipe operating on a 15-minute cleaning cycle subject to chlorination of 1 ppm total chlorine residual for 15 minutes daily kept the Rf near target levels. Further study is needed to verify effects of short-term problems affecting ball movement.

(3) Chlorination. Chlorine alone significantly delayed increases in Rf. Initial results of "shock" chlorination indicated the potential value of this technique for returning fouled pipes to acceptable Rfs.

b. Titanium Pipe

(1) Flow-Driven Brushes. Both 28-mm diameter brushes were effective in preventing Rf increases when the pipe was cleaned on 4-, 6-, or 8-hour intervals. The 29-mm brush was not effective in preventing Rf increases in comparison to the results reported for aluminum.

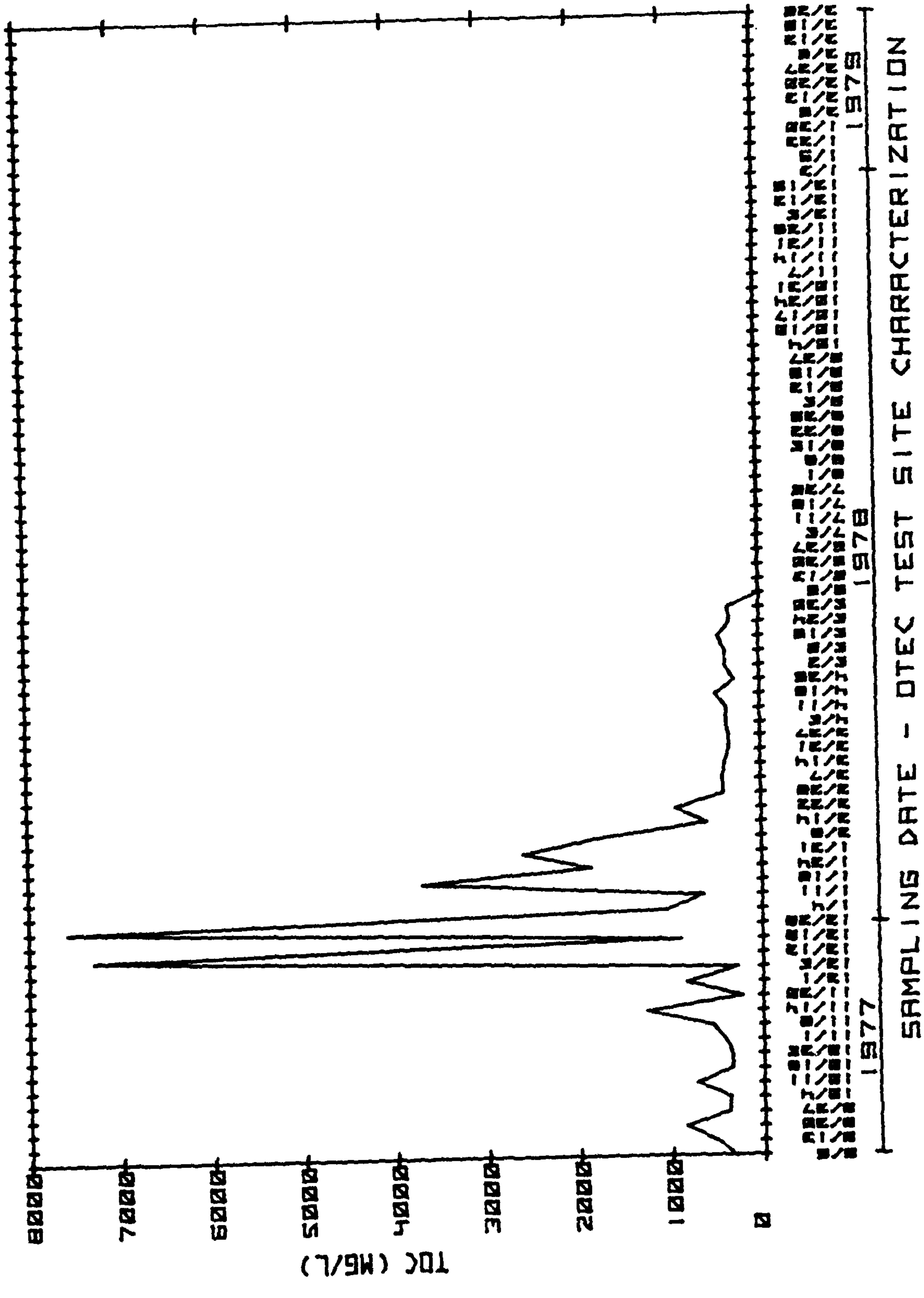
(2) Recirculating Sponge Rubber Balls. Sponge rubber balls performed well when the pipe was cleaned at 15-, 30-, and 60-minute cycles. Chlorine addition extended the cycle interval to 120 minutes.

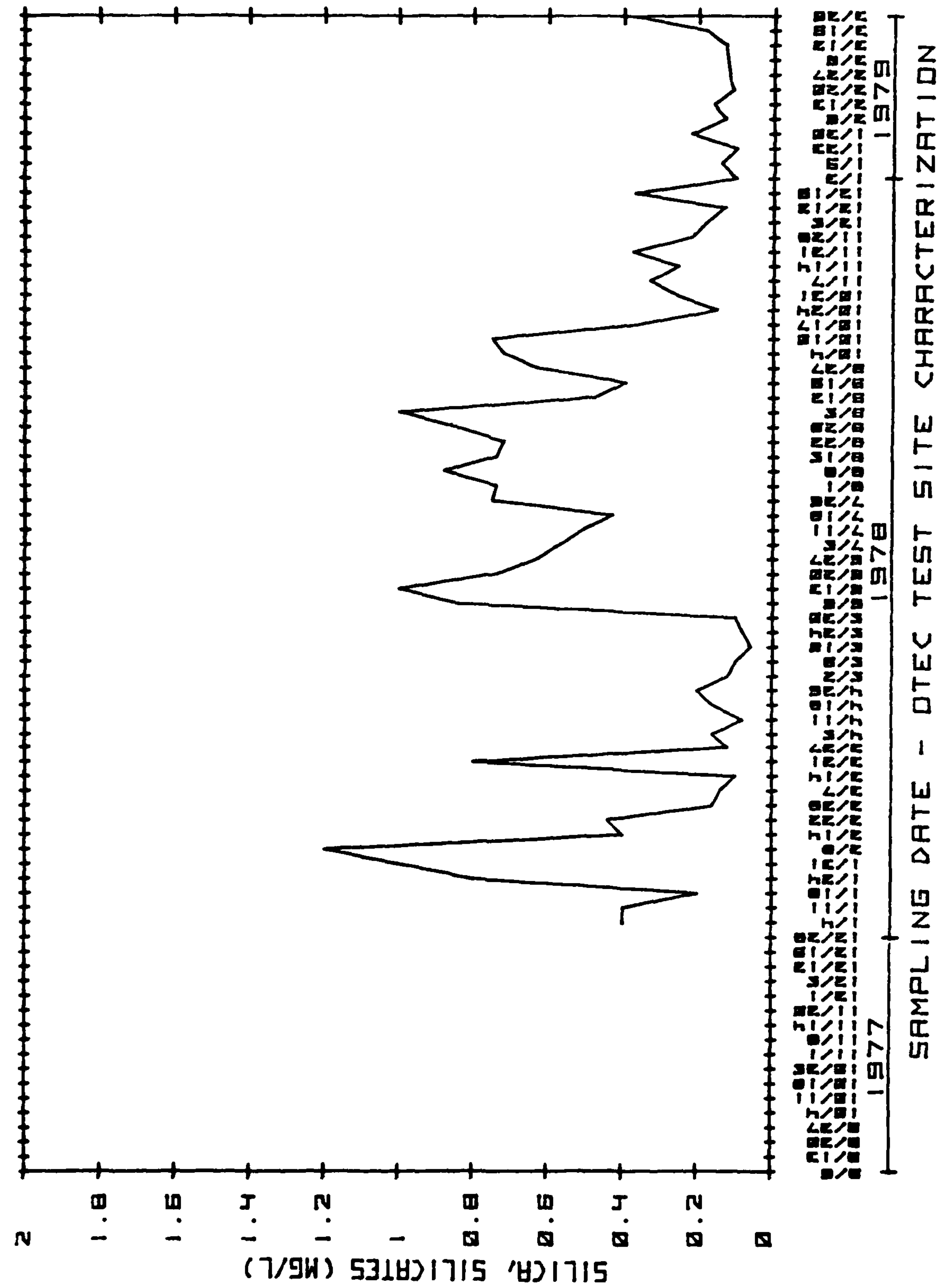
(3) Chlorination. A 0.5 ppm total chlorine residual kept the Rf below target levels for 156 days. Doubling the residual had no effect on the Rf.

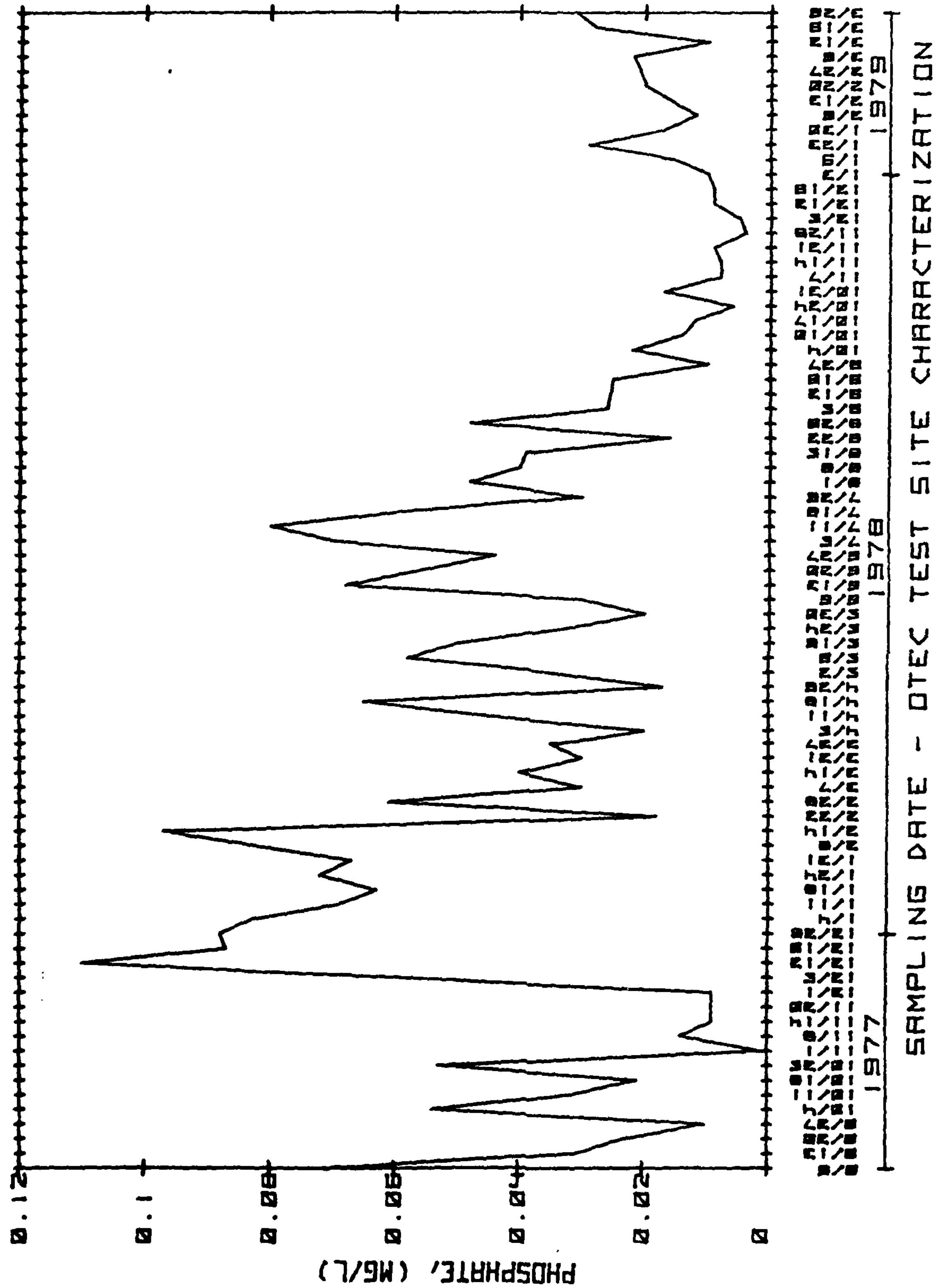
In conclusion, the prospects are good for maintaining the heat exchanger efficiency so critical to the success of OTEC. Further work is required, however, to study specific questions raised in field tests such as seasonal effects of fouling, duration of cleaning effectiveness by candidate cleaning systems, and chlorine's startling effectiveness at low dosages.

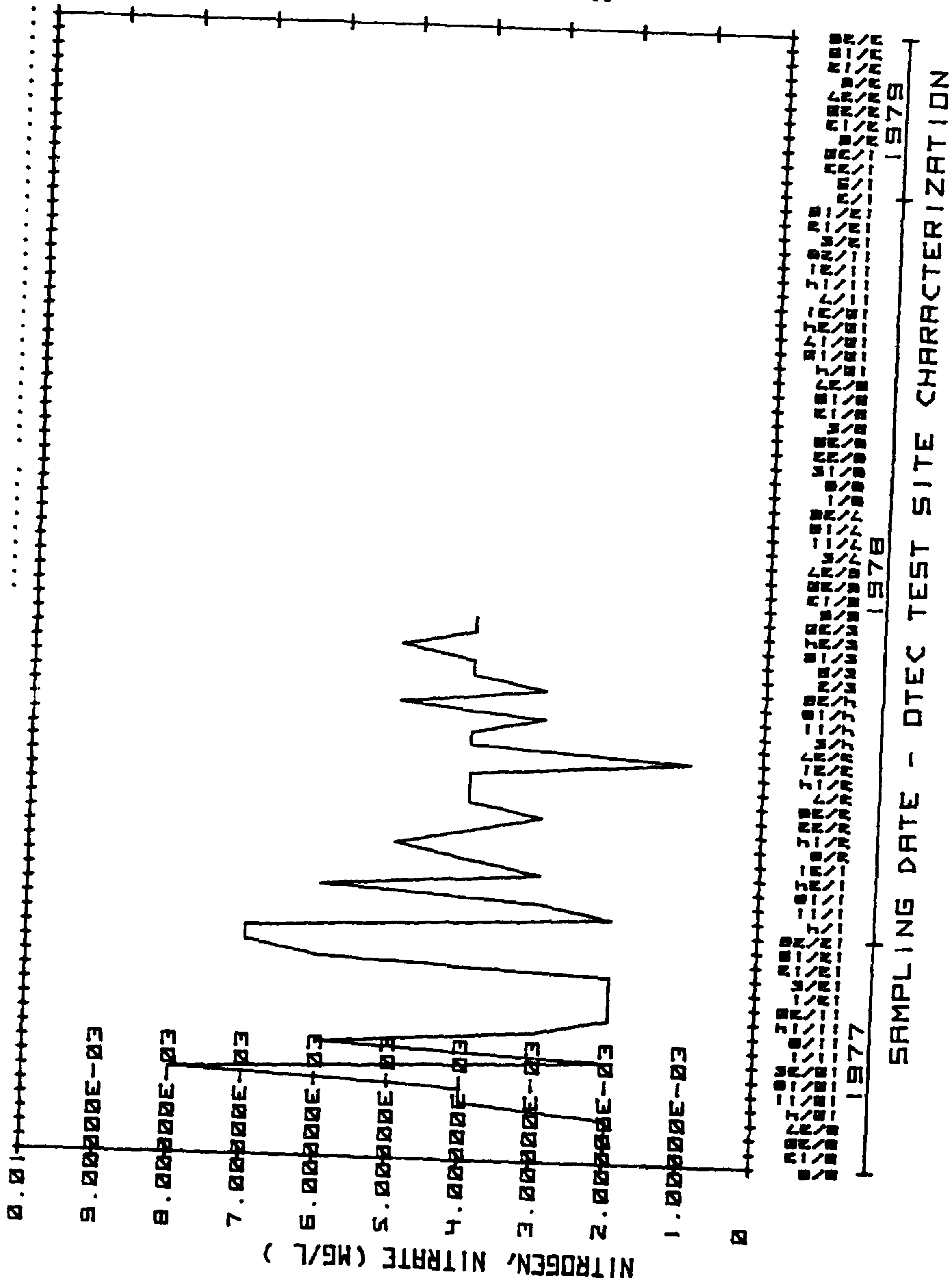
APPENDIX A

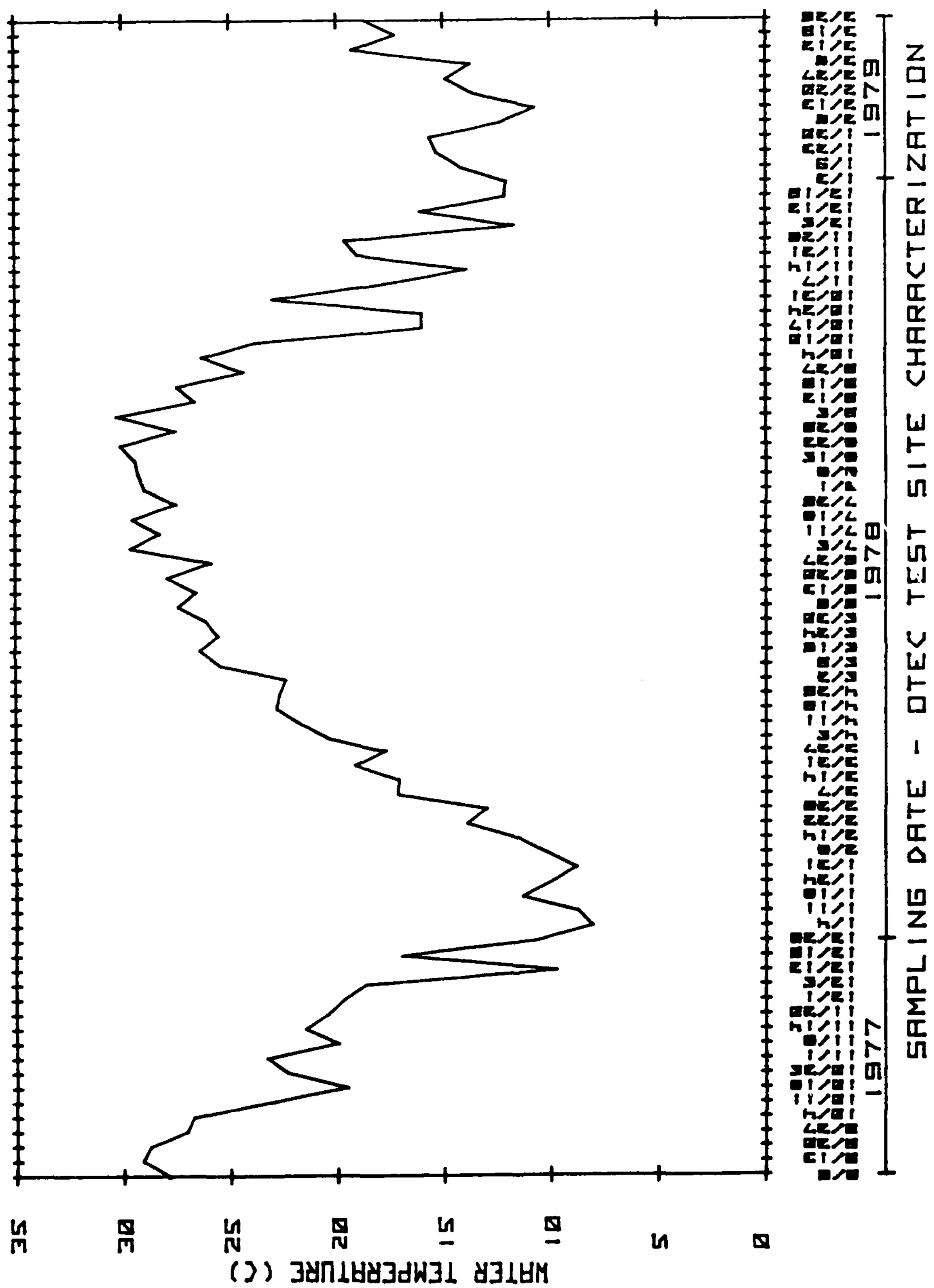
WATER QUALITY AT OTEC TEST SITE


TOC (MG/L)
0
1000
2000
3000
4000
5000
6000
7000
8000
1977
1978
1979
SAMPLING DATE - OTEC TEST SITE CHARACTERIZATION


SILICA, SILICATES (MG/L)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
1977
1978
1979
SAMPLING DATE - OTEC TEST SITE CHARACTERIZATION


SAMPLING DATE - OTEC TEST SITE CHARACTERIZATION
PHOSPHATE, (MG/L)
0
0.02
0.04
0.06
0.08
0.1
0.12
1977
1978
1979

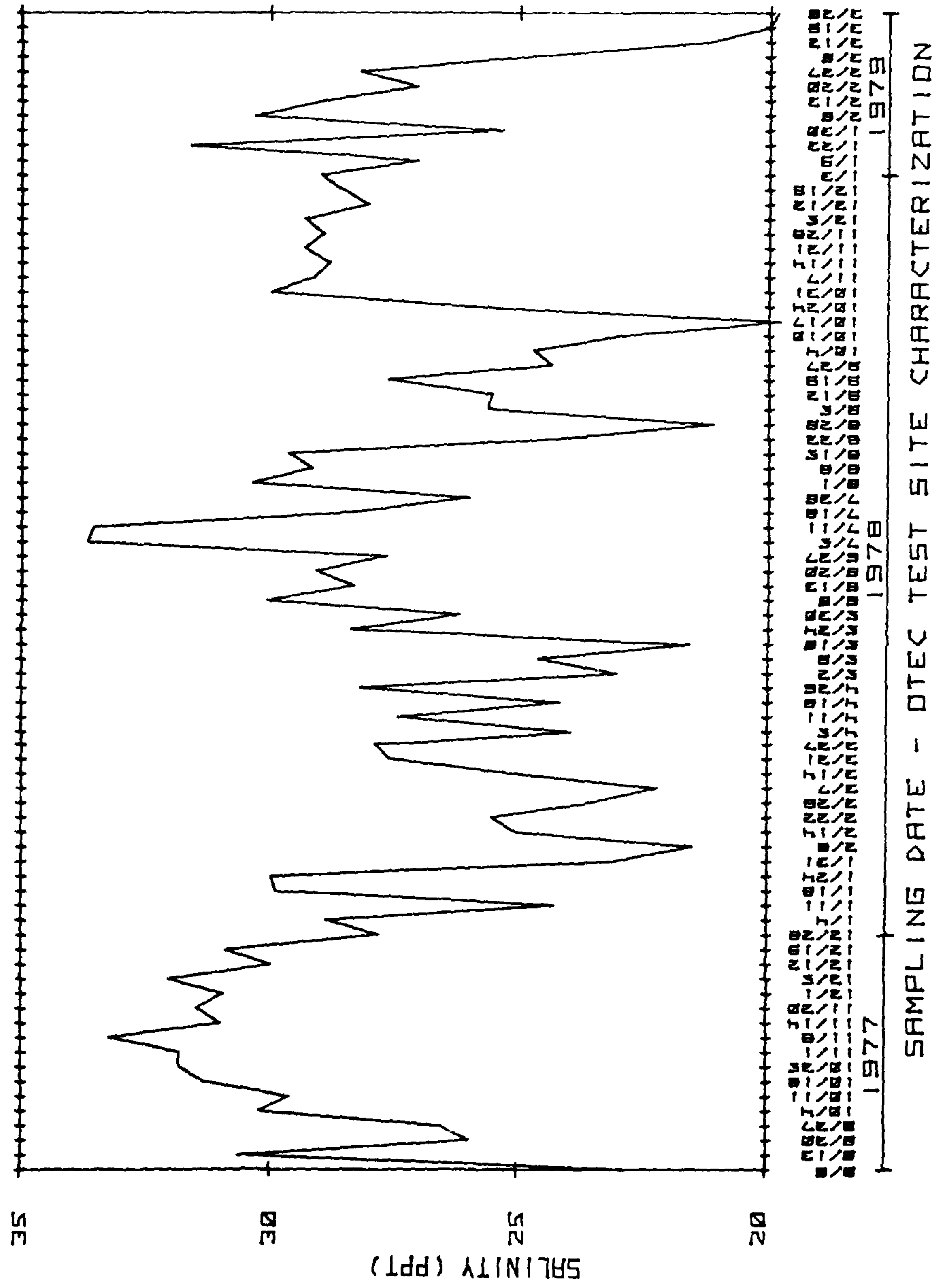

SAMPLING DATE - OTEC TEST SITE CHARACTERIZATION
NITROGEN, NITRATE (MG/L)
1977
1978
1979
0.01
9.00000E-03
8.00000E-03
7.00000E-03
6.00000E-03
5.00000E-03
4.00000E-03
3.00000E-03
2.00000E-03
1.00000E-03
0

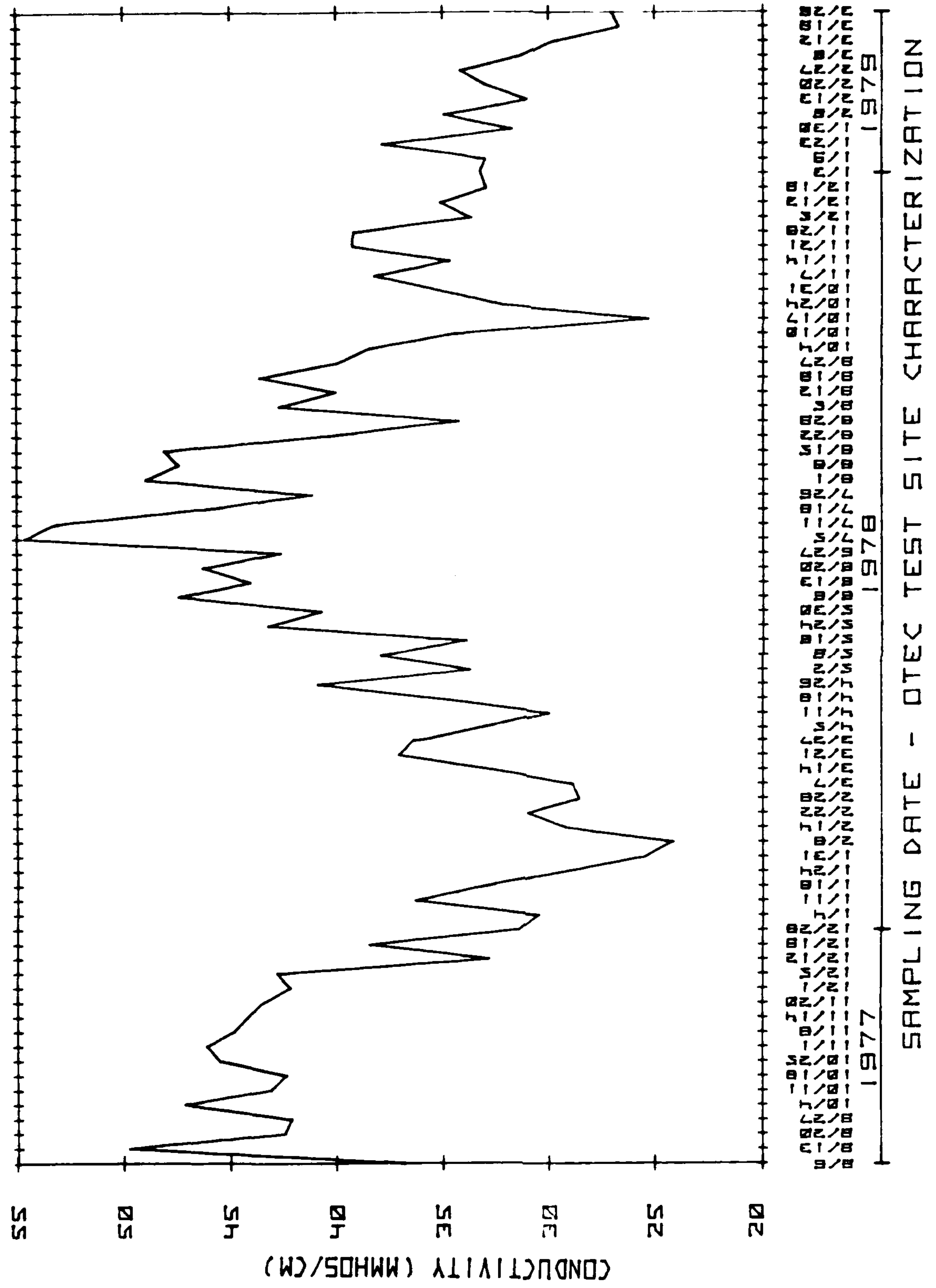

WATER TEMPERATURE (C)
0
5
10
15
20
25
30
35
1977
1978
1979
SAMPLING DATE - OTEC TEST SITE CHARACTERIZATION

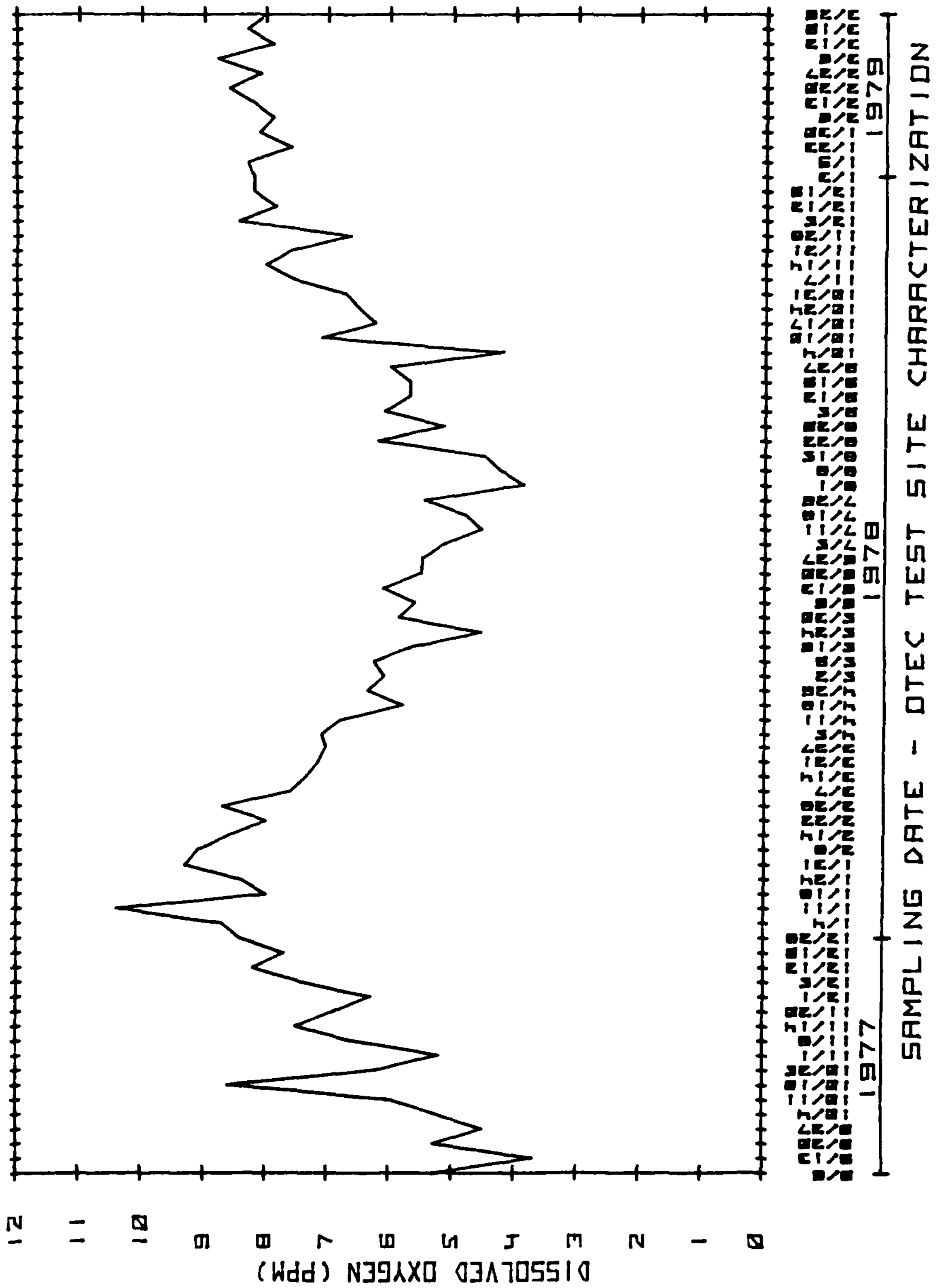
AD-A096 343   NAVAL COASTAL SYSTEMS CENTER PANAMA CITY FL   F/G 13/1
TEST RESULTS OF HEAT EXCHANGER CLEANING IN SUPPORT OF OCEAN THE--ETC(U)
DEC 80   D F LOTT   IAA-ET-78-01-3218
UNCLASSIFIED   NCSC-TM-298-80

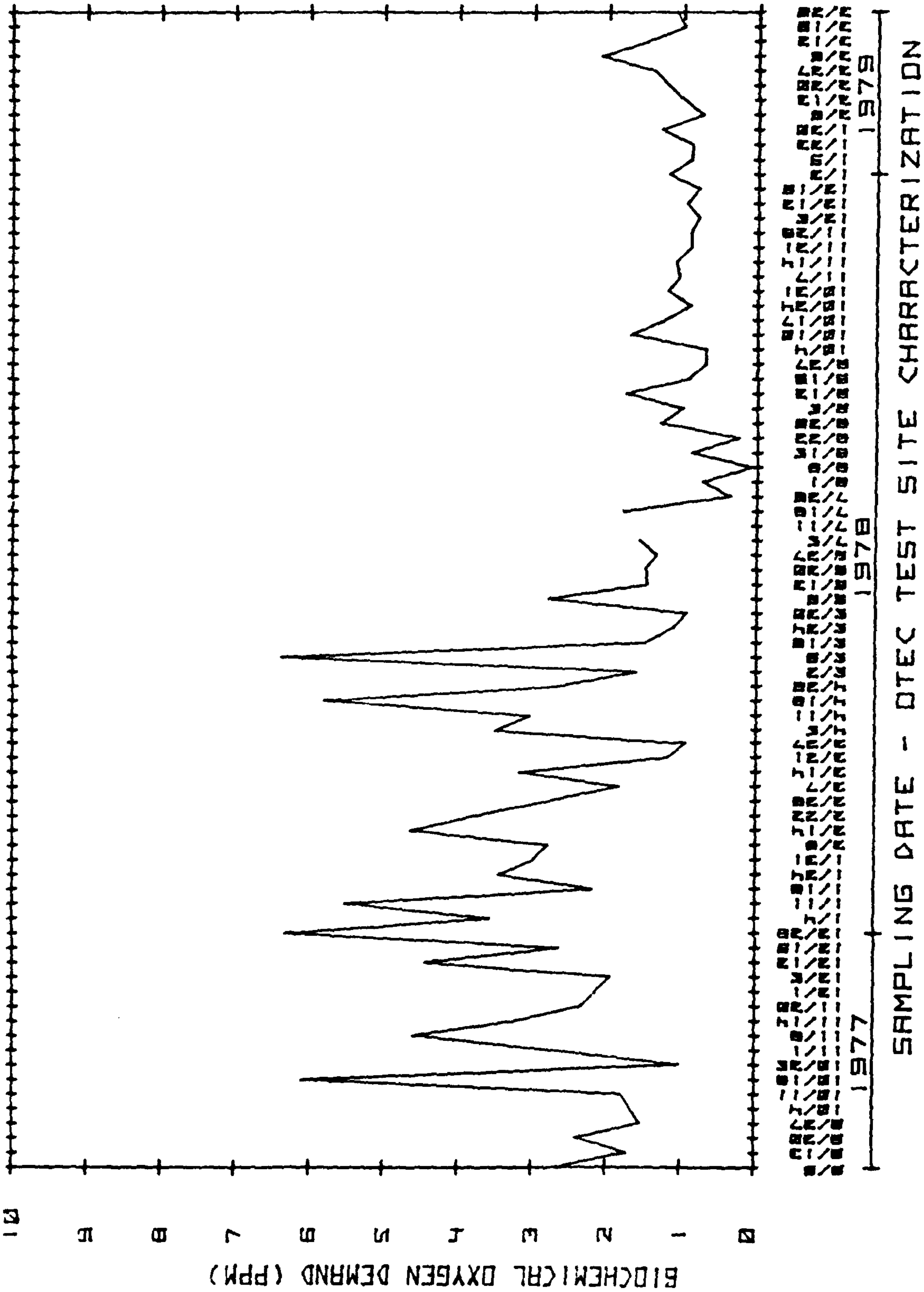
2 OF 3

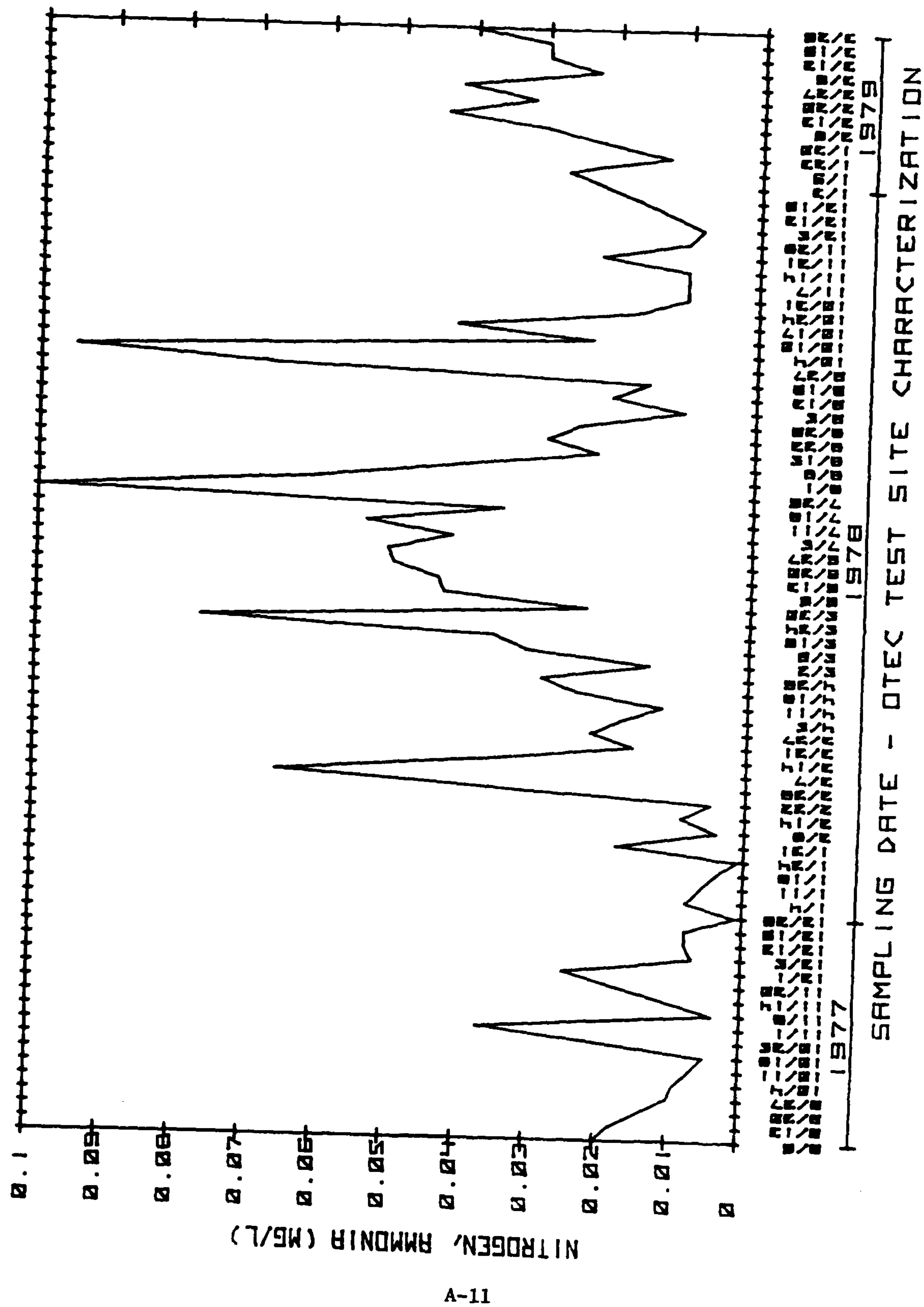
AD A
098343

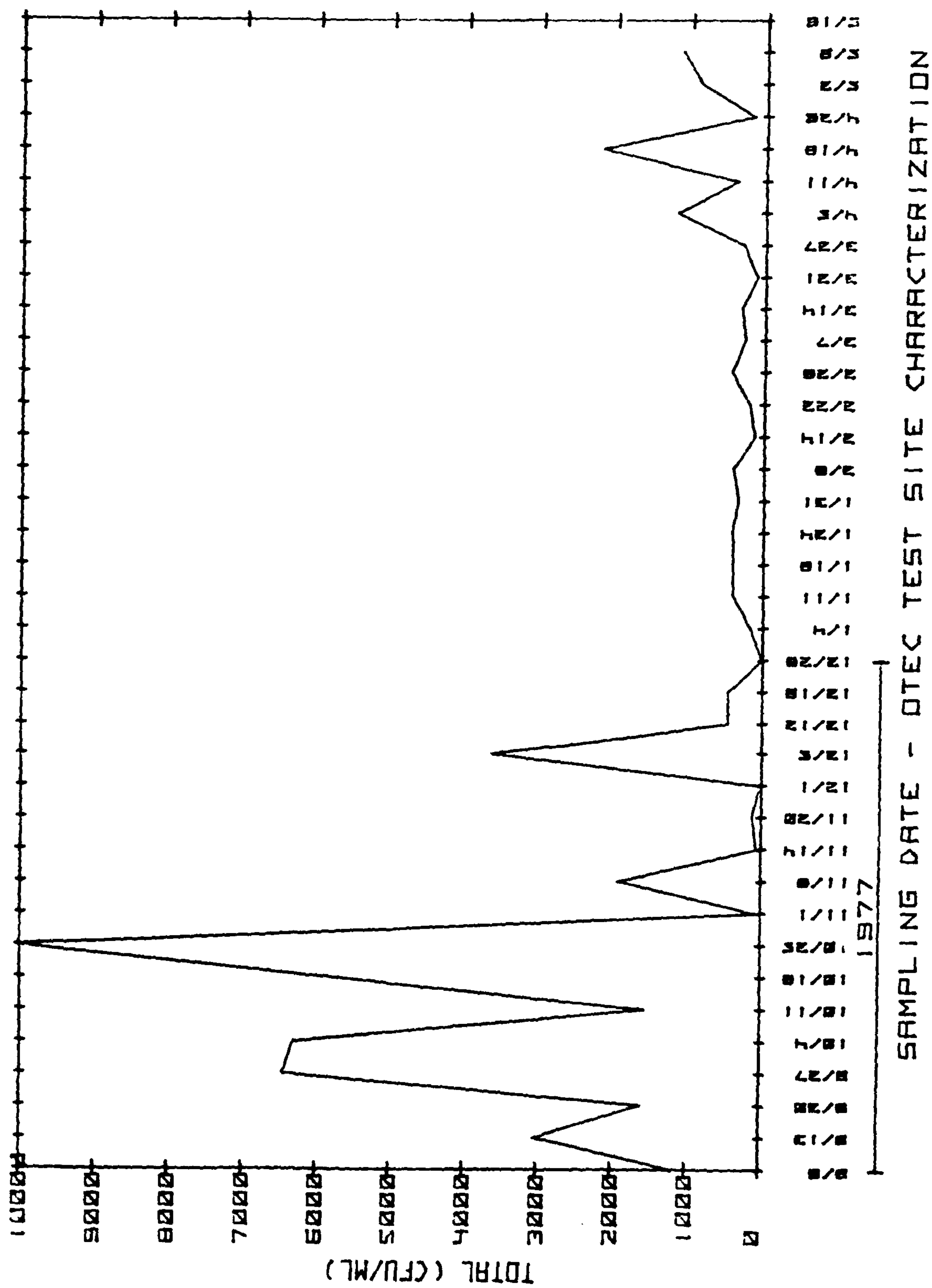

SAMPLING DATE - OTEC TEST SITE CHARACTERIZATION
SALINITY (PPT)
35
30
25
20
1977
1978
1979

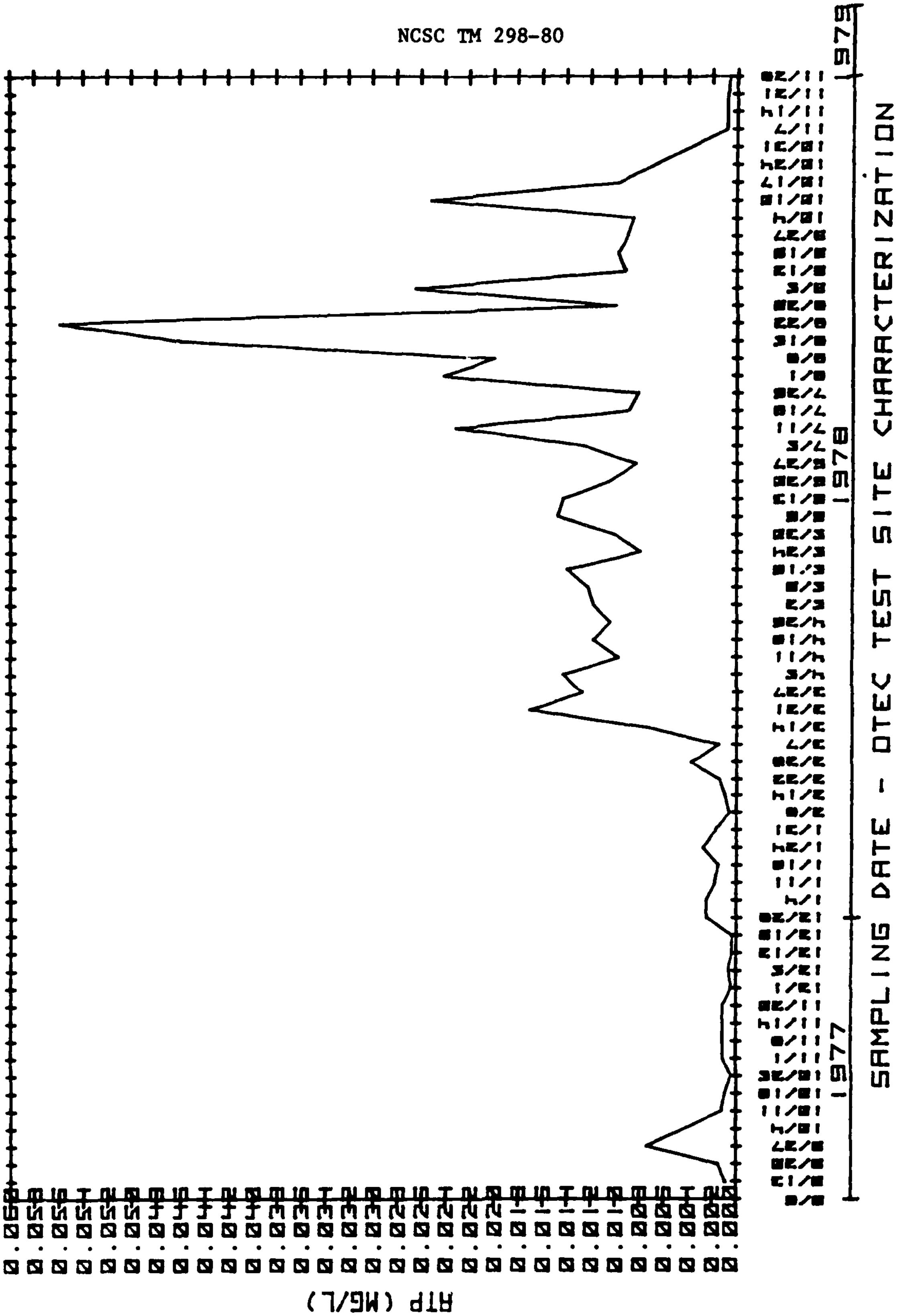

SAMPLING DATE - OTEC TEST SITE CHARACTERIZATION
1977
1978
1979
CONDUCTIVITY (MMHOS/CM)
55
50
45
40
35
30
25
20

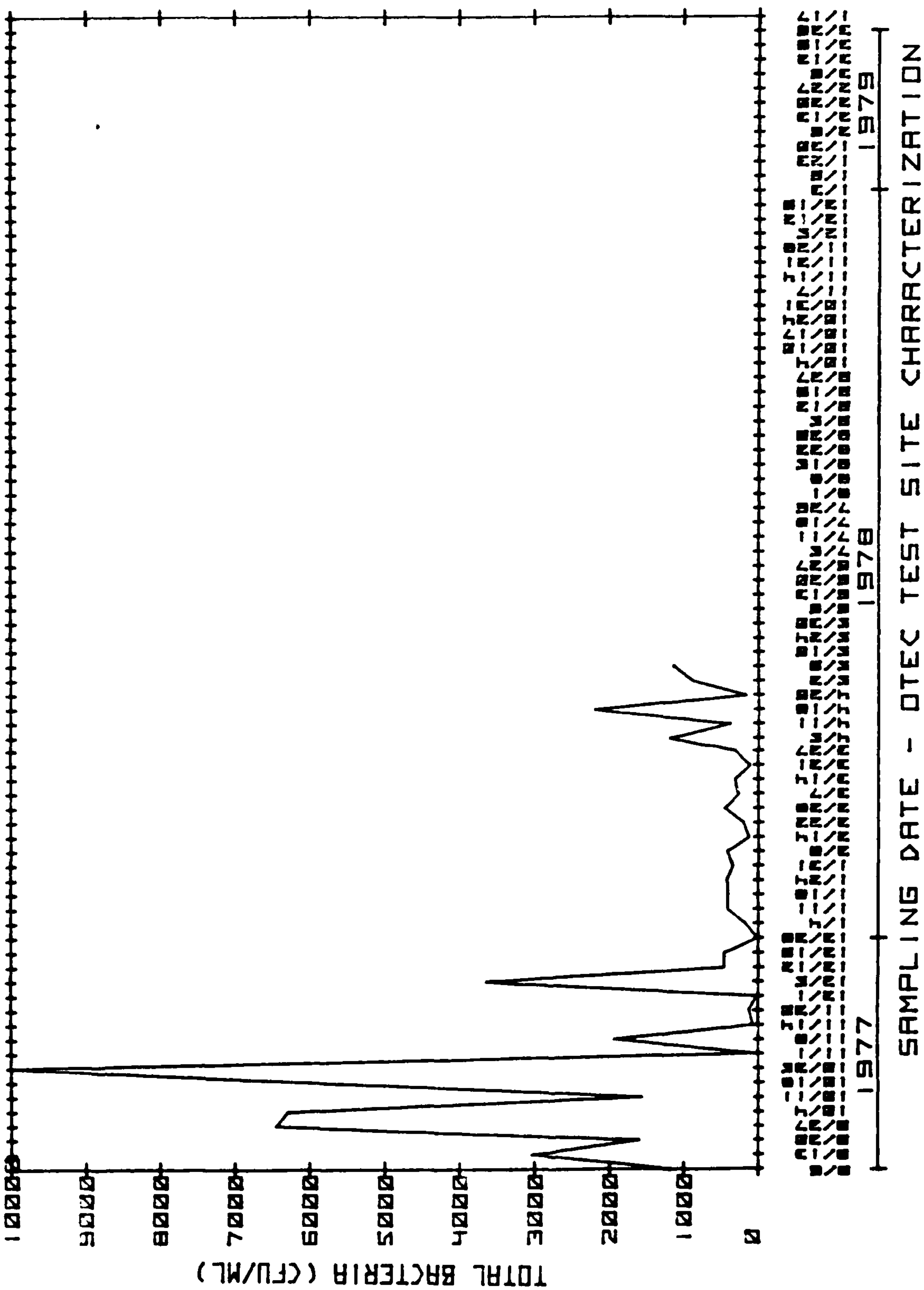

DISSOLVED OXYGEN (PPM)
0
1
2
3
4
5
6
7
8
9
10
11
12
SAMPLING DATE - OTEC TEST SITE CHARACTERIZATION
1977
1978
1979

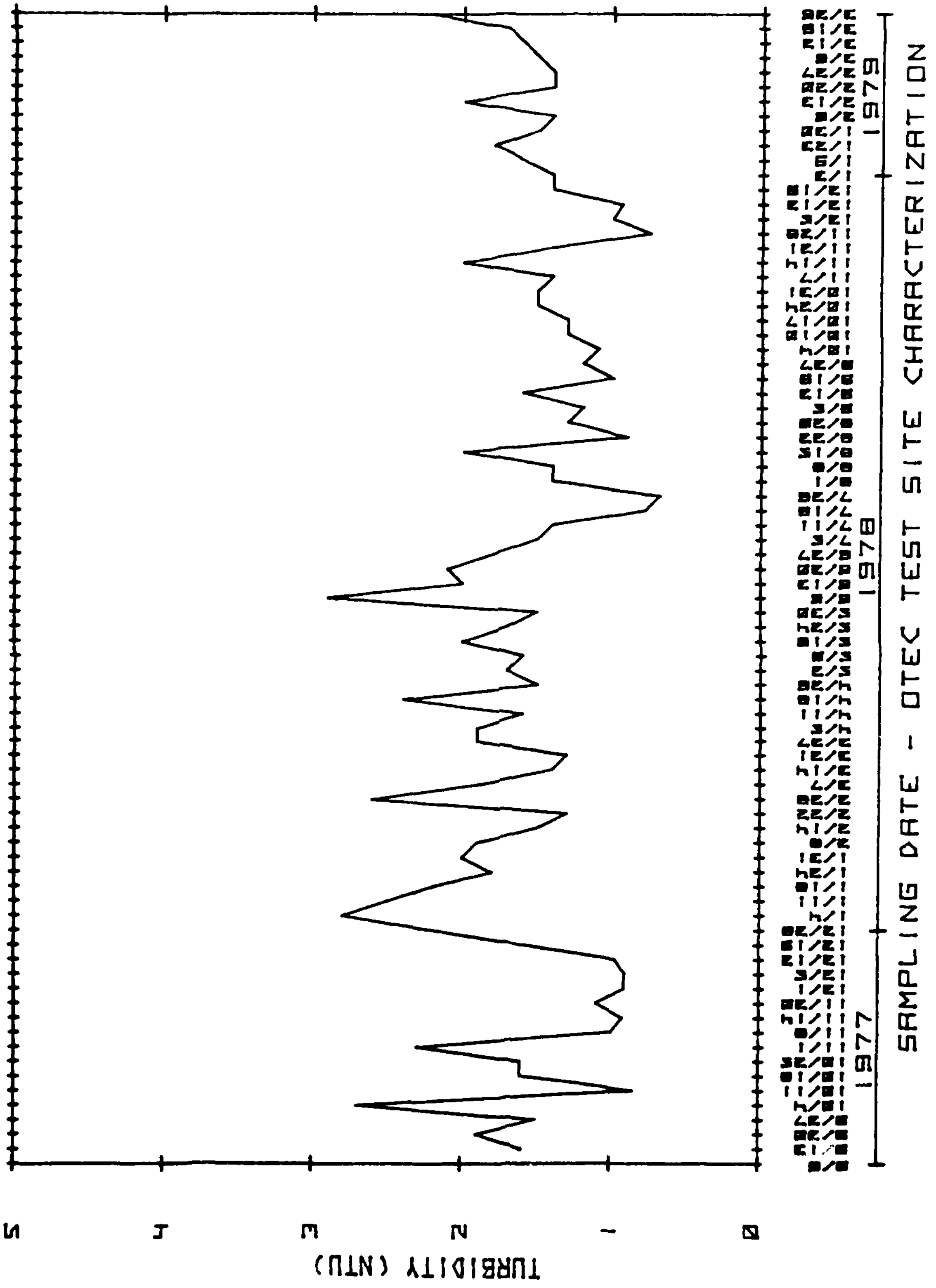

SAMPLING DATE - OTEC TEST SITE CHARACTERIZATION
1977
1978
1979
BIOCHEMICAL OXYGEN DEMAND (PPM)

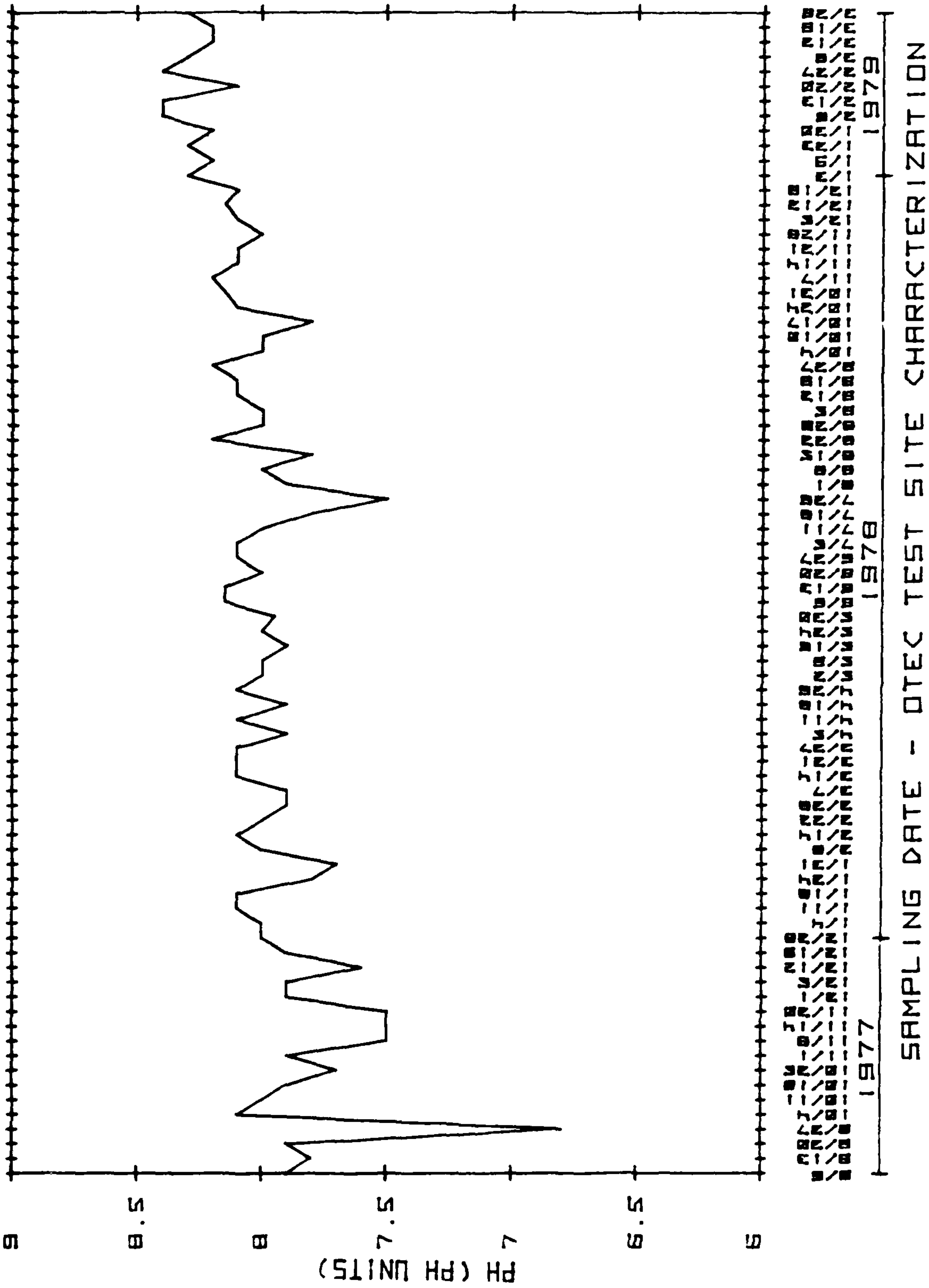

NITROGEN, AMMONIA (MG/L)
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
1977
1978
1979
SAMPLING DATE - OTEC TEST SITE CHARACTERIZATION


SAMPLING DATE - OTEC TEST SITE CHARACTERIZATION
1977
TOTAL (CFU/ML)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000


SAMPLING DATE - OTEC TEST SITE CHARACTERIZATION
ATP (MG/L)
1977
1978
1979


TOTAL BACTERIA (CFU/ML)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
1977
1978
1979
SAMPLING DATE - OTEC TEST SITE CHARACTERIZATION


SAMPLING DATE - OTEC TEST SITE CHARACTERIZATION
1977
1978
1979
TURBIDITY (NTU)
0
1
2
3
4
5


SAMPLING DATE - OTEC TEST SITE CHARACTERIZATION
PH (PH UNITS)
1977
1978
1979

APPENDIX B

WILSON PLOTS FOR 1979 AND 1979-80 FIELD EXPERIMENT

Appendix B contains Wilson Plots performed during the 1979 and 1979-80 field experiments. Each Wilson Plot for the clean tube defines the non-biological resistances inherent in the heat transfer monitor. These resistances are determined by the 1/H intercept when 1/H is plotted versus v (-0.8) and data is subject to linear regression. Ideally, the intercept should be zero but in practice the value approaches 0.75 to 1.5 X 10^{-3} ft^2-hr-^{0}F/BTU. Line slope should remain constant for a particular tube and biofouling will offset the 1/H intercept to a value greater than that seen over the clean tube state.

A comparison of Wilson Plots obtained for clean and fouled tubes (Page B-4 to B-11) indicated that a majority of the tubes conform to theory. Variations in line slope occurred that were attributed to accuracy of flow measurement. Deviations in flow accuracy are of greater signifiance at high rather than low flow rates and thus cause a steeper line slope when plotted. Flow accuracy in sonic flowmeters is affected by flowmeter drift, acoustic noise, bubble formation, and the sonic coupling compound located between the flowmeter and pipe section.

Tubes 7 and 8, page B-10 and B-11, respectively, do not conform to theory. The fouled tubes show a decrease in the 1/H intercept when compared to the clean tube state. This problem has been reported previously. The technique for heat transfer measurement assumes that system contact resistances remain constant during a test. However, it is likely that the constant heating and cooling of HTM's, the mechanical cleaning of pipe sections, handling the test units, or corrosion development between heaters and tube walls could change the initial contact resistance.

Comparisons of clean tubes following periodic chemical cleaning are included for Tubes 1 - 10, pages B-12 through B-21, respectively. The graphs show that the non-biological resistances fall within a narrow range for a particular tube. The range probably results from the formation of an inorganic scale (i.e., corrosion gel) that is resistant to chemical and/or mechanical cleaning.

Finally, individual Wilson Plots are found in pages B-22 through B-96. These plots show the spread of data used for calculation of slope and intercept for individual tubes and form the zero baseline for calculation of fouling resistance.

TABLE B-1

LIST OF WILSON PLOTS PERFORMED DURING THE

1979 AND 1979-80 FIELD EXPERIMENTS

DATE	TUBES	COMMENT
10 May 1979	1 - 8	Clean Tubes - Beginning of 1979 Experiment
9 Jul 1979	1 - 8	Fouled Tubes - End of 1979 Experiment
13 Jul 1979	1 - 8	Clean Tubes - Test aborted due to electrical storm on 17 July 1979
26 Jul 1979	1 - 8	Clean Tubes - Test aborted due to electrical storm on 5 August 1979
14 Aug 1979	1 - 8	Clean Tubes - test aborted due to pump failure on 25 August 1979
19 Sep 1979	1 - 10	Clean - Beginning of 1979-80 Experiment
3 Oct 1979	10	Clean
10 Dec 1979	5 and 9	Fouled - 9 not cleaned. In preparation for chlorination
11 Dec 1979	5	Clean - Restarted on 4-hour cycle, clean tube with intermittant chlorination
8 Jan 1980	5, 7 - 9	Fouled Tubes - 7 changed to 15-minute cycle. 8 connected to chlorination
7 Feb 1980	5 - 10	Fouled Tubes - 6 connected to chlorine 10 ⟶ 8 ⟶ 6 ⟶ overboard 9 ⟶ 5 ⟶ 7 ⟶ overboard
13 Feb 1980	5 and 7	Clean Tubes. 1.15-inch brush added to 5 (4-hour cycle), 7 has 29mm "soft" ball on a 15-minute cycle with chlorination
18 Mar 1980	6	Fouled Tube - Chlorine concentration doubled
30 Mar 1980	1 and 2	Fouled Tubes - Preparation for end of field tests
31 Mar 1980	3 - 5 8 - 10	Fouled Tubes - End of field tests

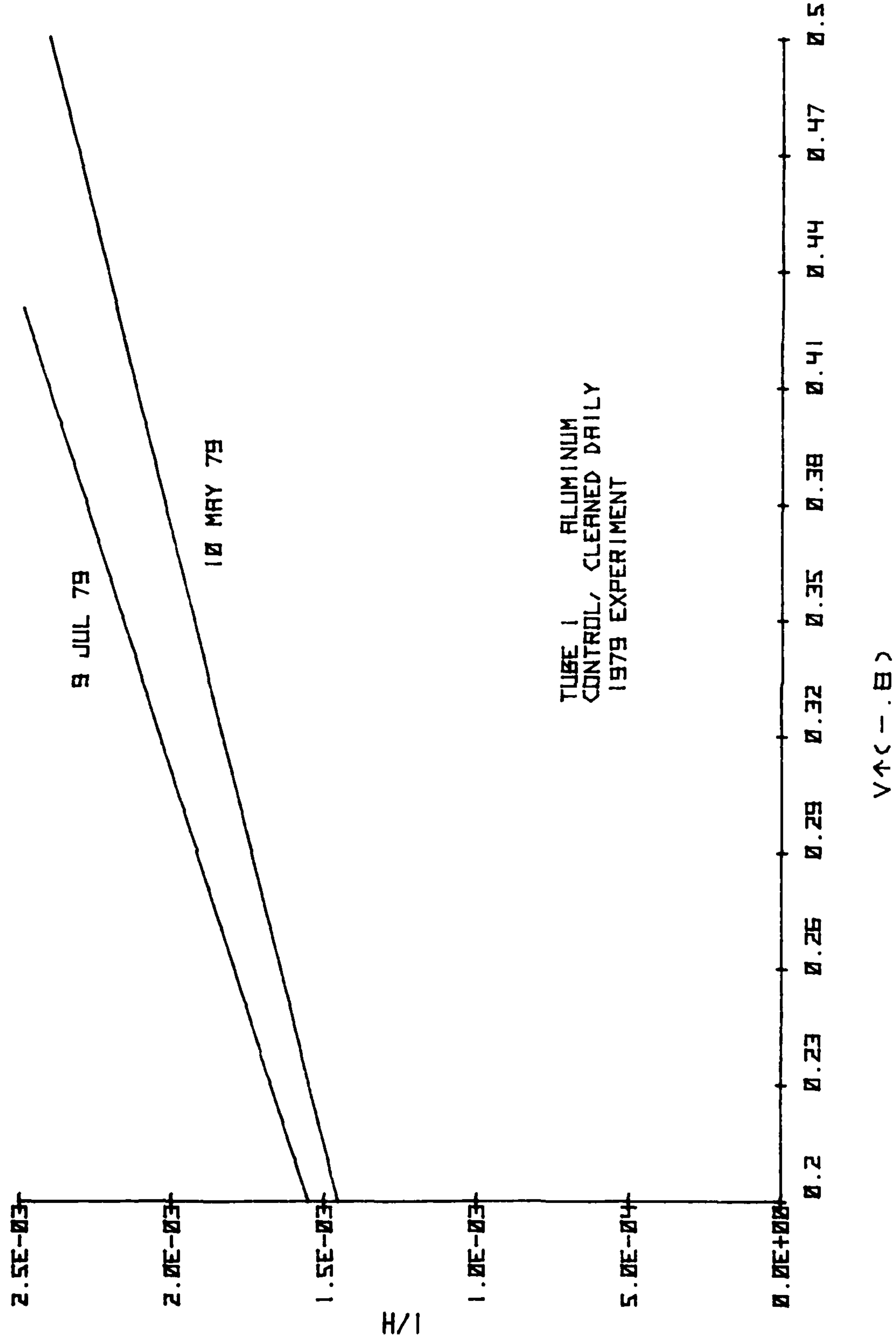

TUBE 1 ALUMINUM
CONTROL, CLEANED DAILY
1979 EXPERIMENT
10 MAY 79
9 JUL 79
H/1
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
2.5E-03
V↑(-.8)
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-1

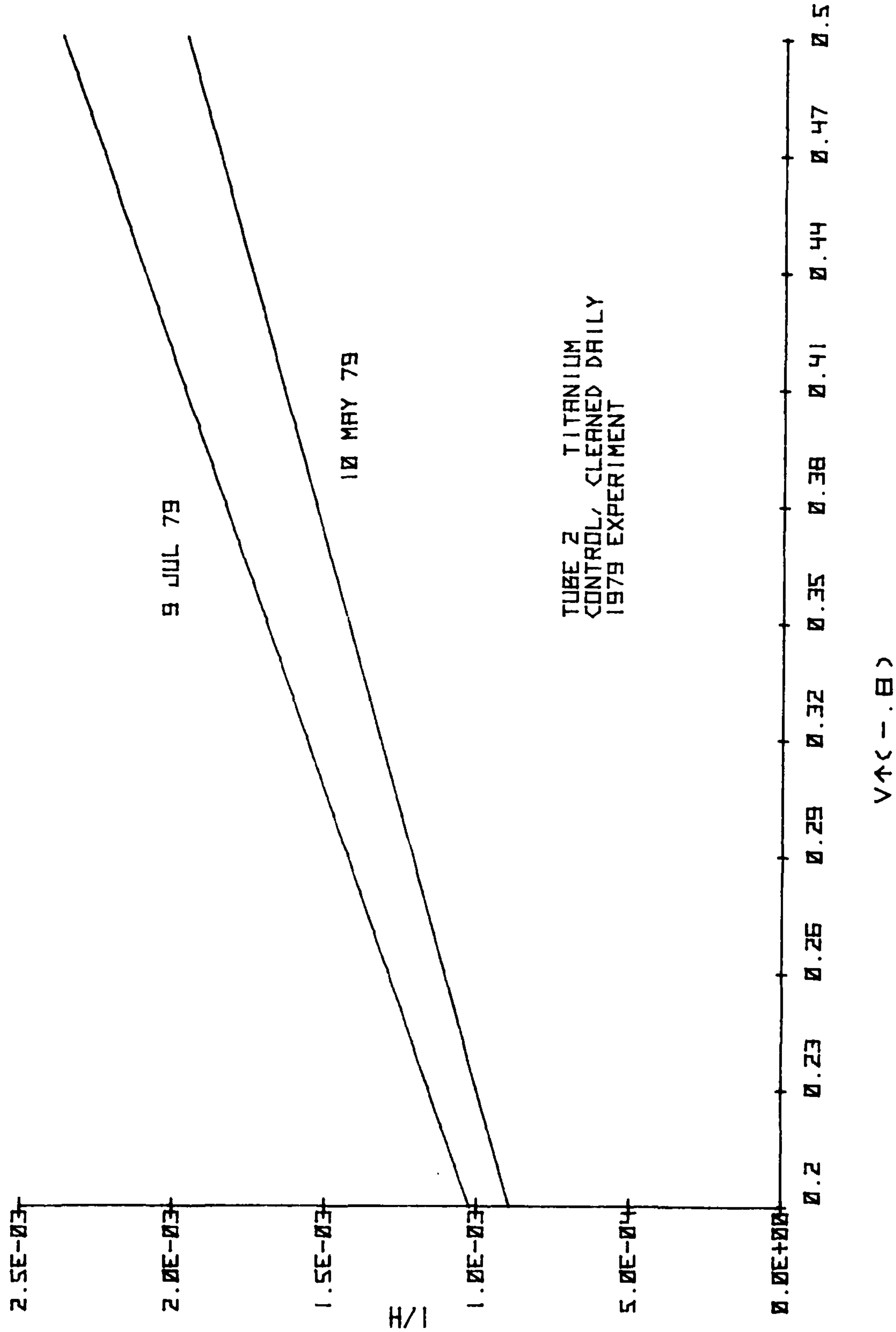

TUBE 2 TITANIUM
CONTROL, CLEANED DAILY
1979 EXPERIMENT
10 MAY 79
9 JUL 79
H/I
V↑(-.8)
2.5E-03
2.0E-03
1.5E-03
1.0E-03
5.0E-04
0.0E+00
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-2

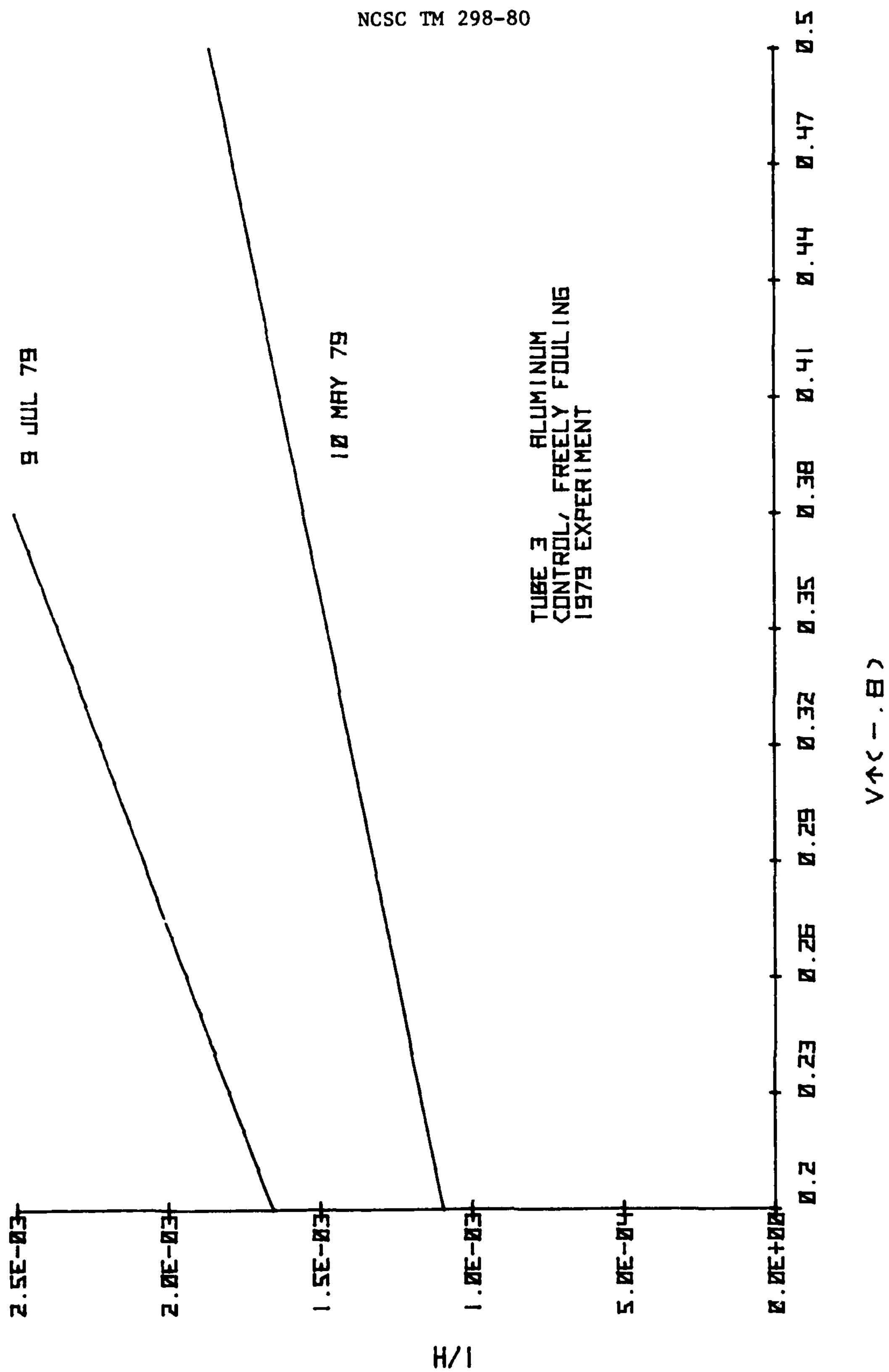

9 JUL 79
10 MAY 79
TUBE 3 ALUMINUM
CONTROL, FREELY FOULING
1979 EXPERIMENT
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
2.5E-03
H/I

FIGURE B-3

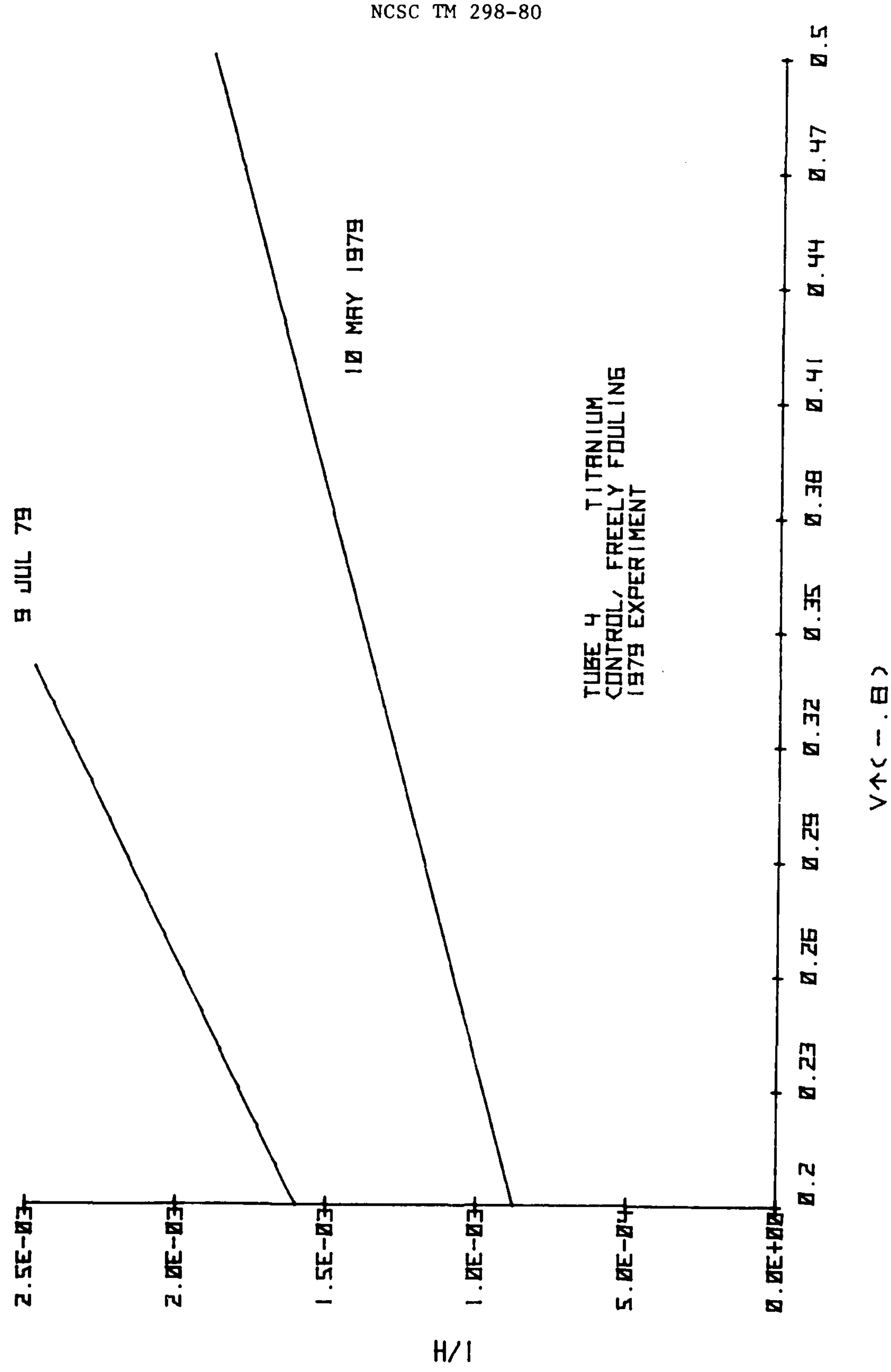

9 JUL 79
10 MAY 1979
TUBE 4 TITANIUM
CONTROL, FREELY FOULING
1979 EXPERIMENT
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
2.5E-03
H/I
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-4

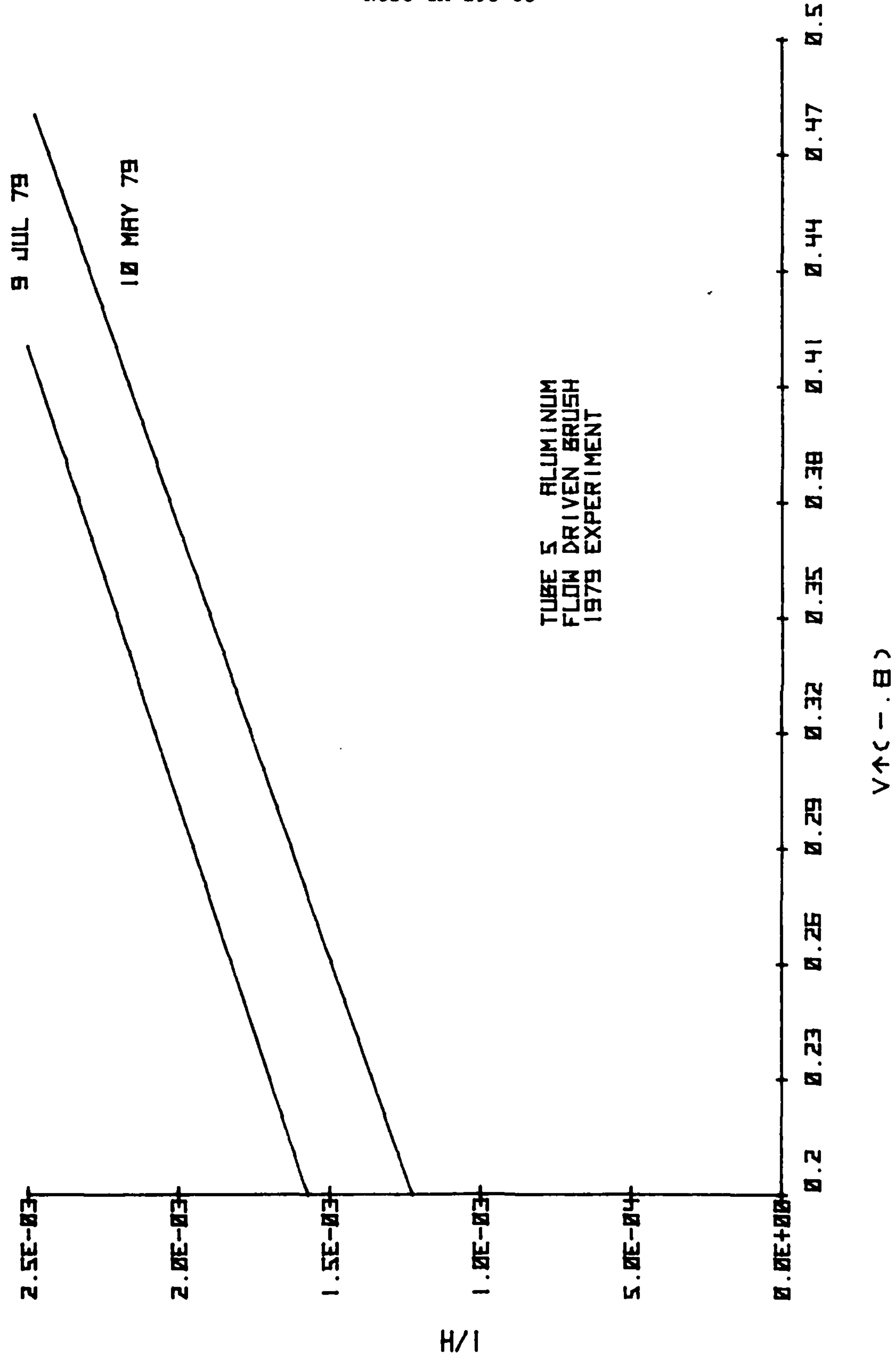

TUBE 5 ALUMINUM
FLOW DRIVEN BRUSH
1979 EXPERIMENT
9 JUL 79
10 MAY 79
H/I
V↑(-.8)
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
2.5E-03
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-5

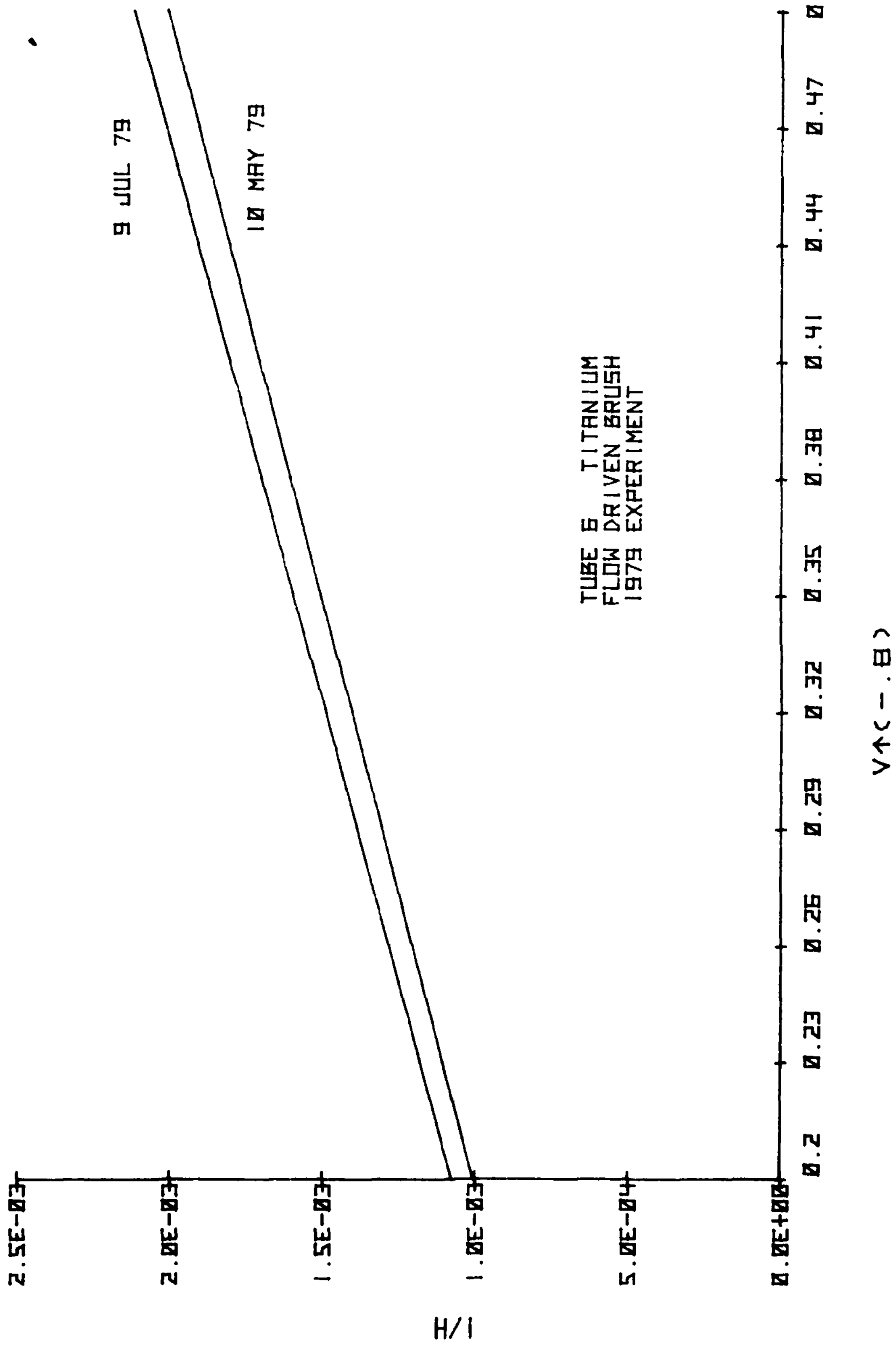

9 JUL 79
10 MAY 79
TUBE 6 TITANIUM
FLOW DRIVEN BRUSH
1979 EXPERIMENT
2.5E-03
2.0E-03
1.5E-03
1.0E-03
5.0E-04
0.0E+00
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)
H/I

FIGURE B-6

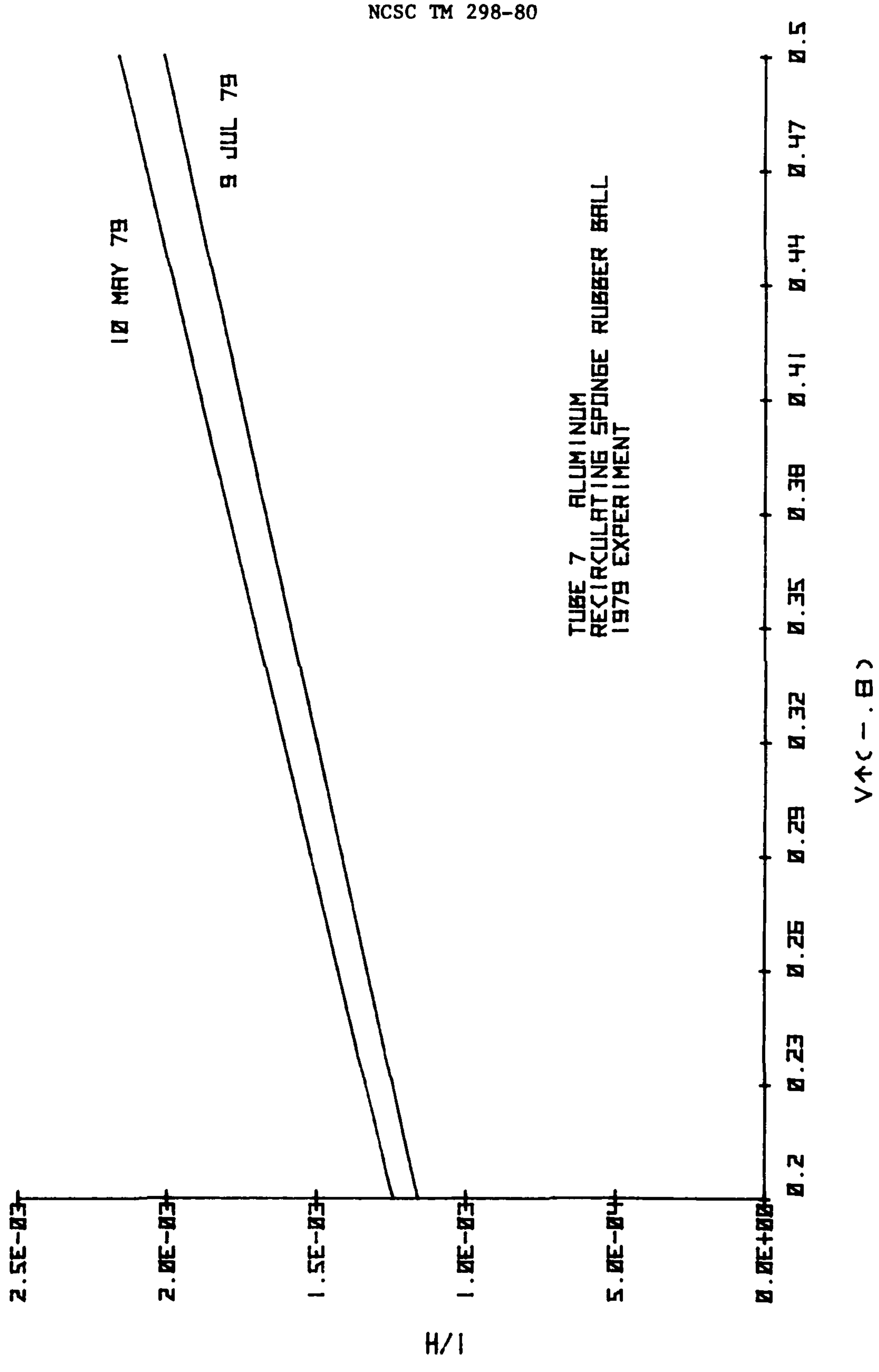

TUBE 7 ALUMINUM
RECIRCULATING SPONGE RUBBER BALL
1979 EXPERIMENT
10 MAY 79
9 JUL 79
2.5E-03
2.0E-03
1.5E-03
1.0E-03
5.0E-04
0.0E+00
H/I
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-7

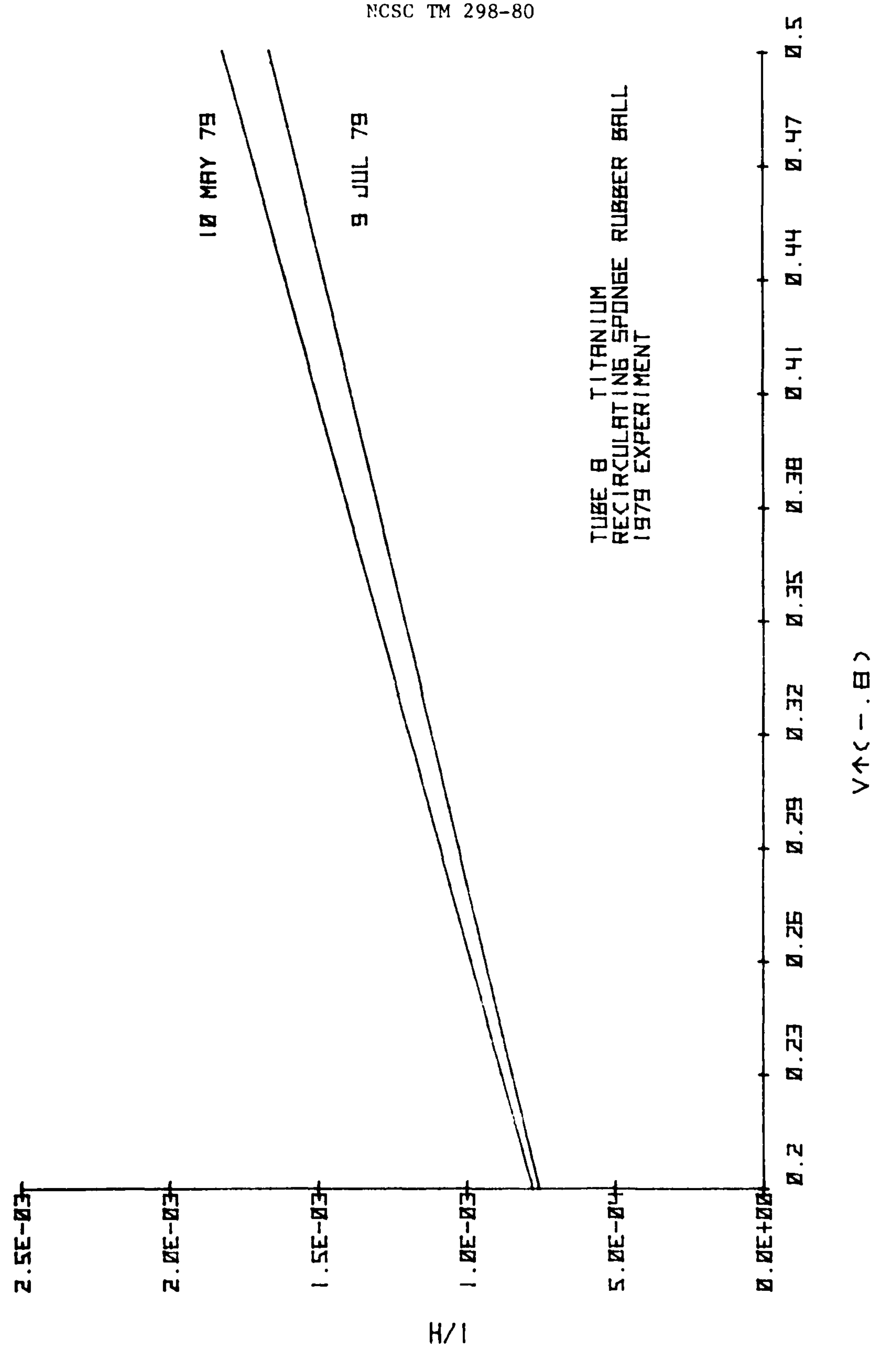

10 MAY 79
9 JUL 79
TUBE 8 TITANIUM
RECIRCULATING SPONGE RUBBER BALL
1979 EXPERIMENT
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
2.5E-03
H/I

FIGURE B-8

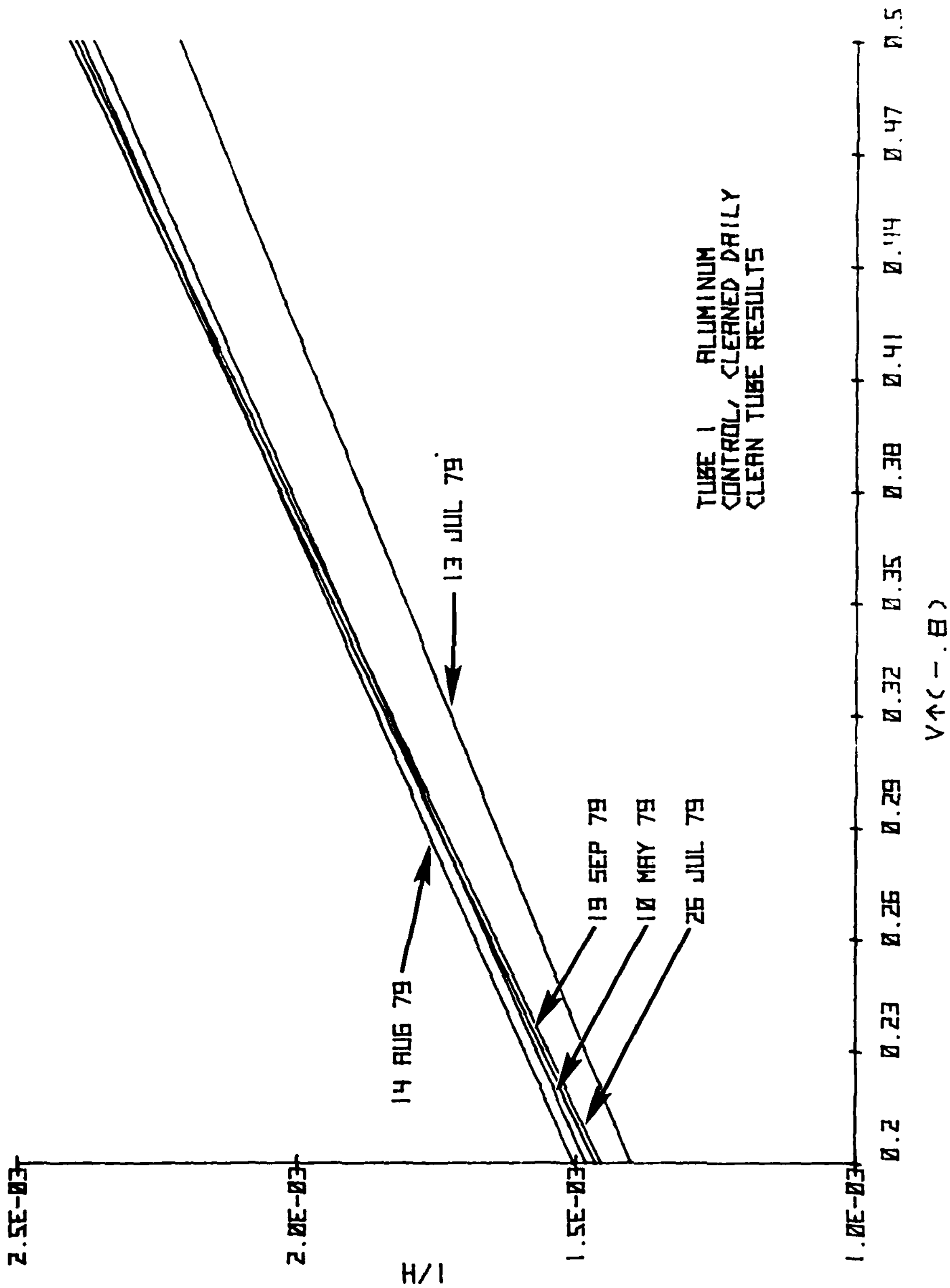

TUBE 1 ALUMINUM
CONTROL, CLEANED DAILY
CLEAN TUBE RESULTS
13 JUL 79
19 SEP 79
10 MAY 79
26 JUL 79
14 AUG 79
H/I
2.5E-03
2.0E-03
1.5E-03
1.0E-03
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-9

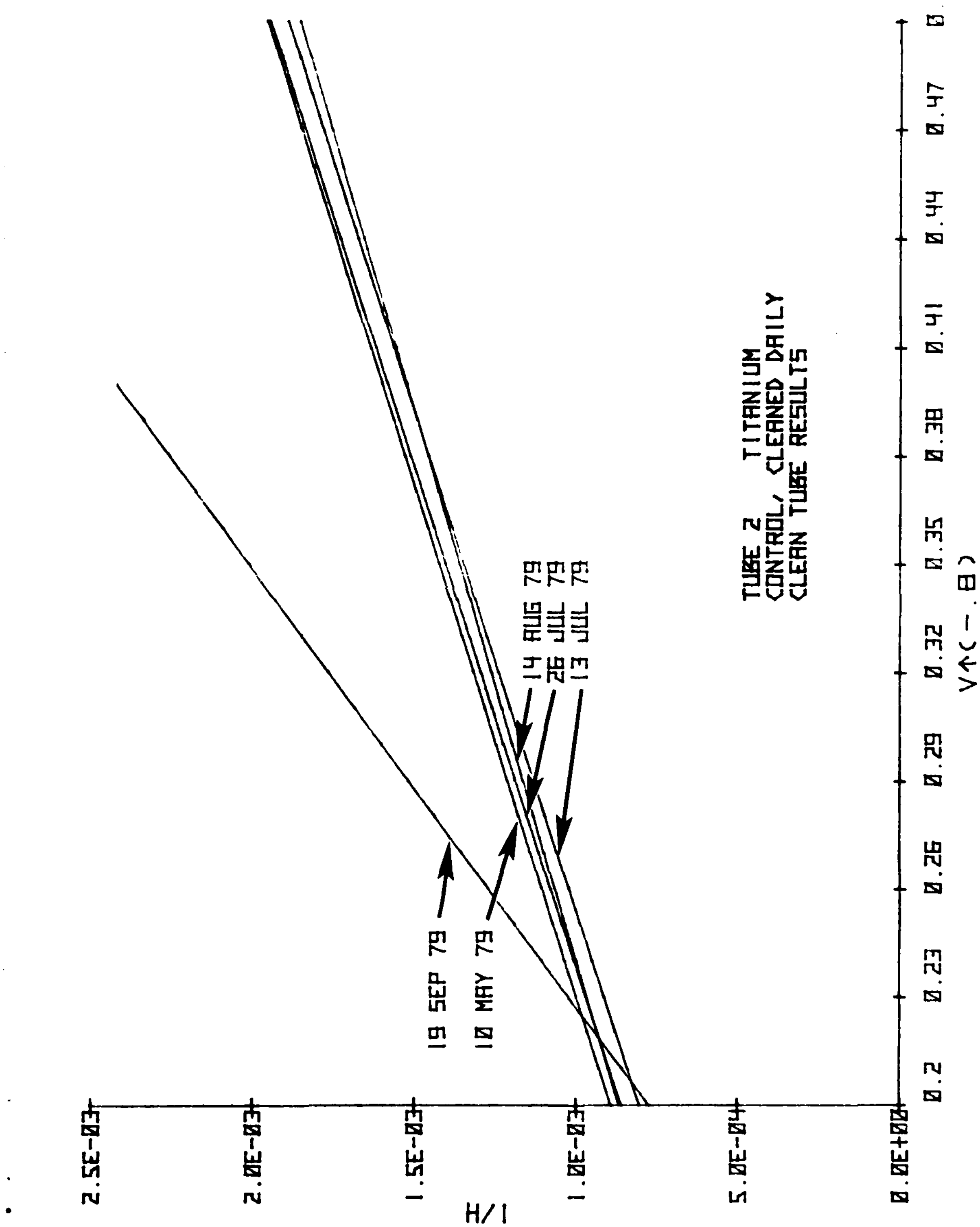

TUBE 2 TITANIUM
CONTROL, CLEANED DAILY
CLEAN TUBE RESULTS
14 AUG 79
26 JUL 79
13 JUL 79
19 SEP 79
10 MAY 79
1/H
V↑(-.8)
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
2.5E-03
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-10

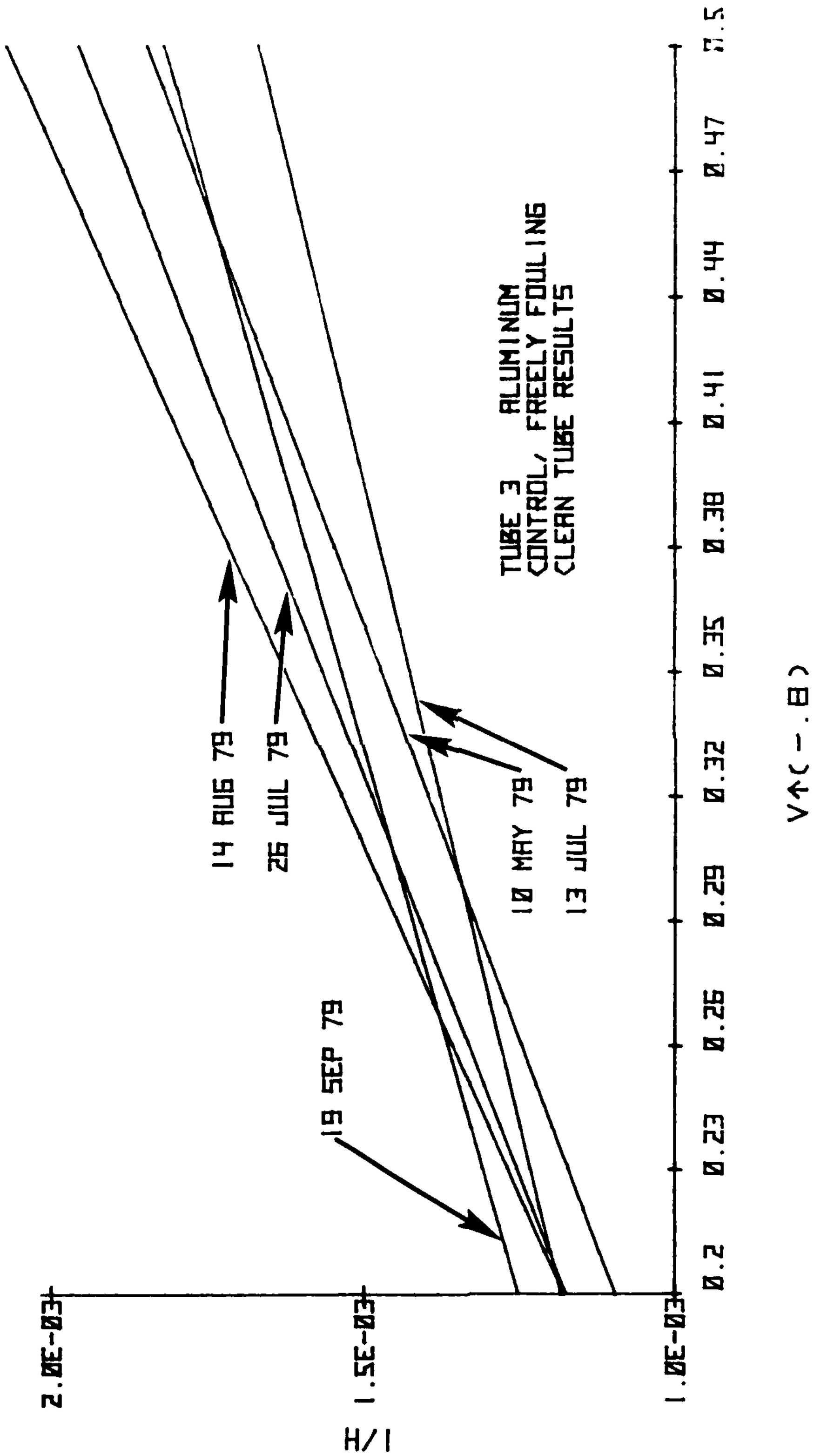

TUBE 3 ALUMINUM
CONTROL, FREELY FOULING
CLEAN TUBE RESULTS
14 AUG 79
26 JUL 79
10 MAY 79
13 JUL 79
19 SEP 79
V↑(-.8)
H/I
2.0E-03
1.5E-03
1.0E-03
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47

FIGURE B-11

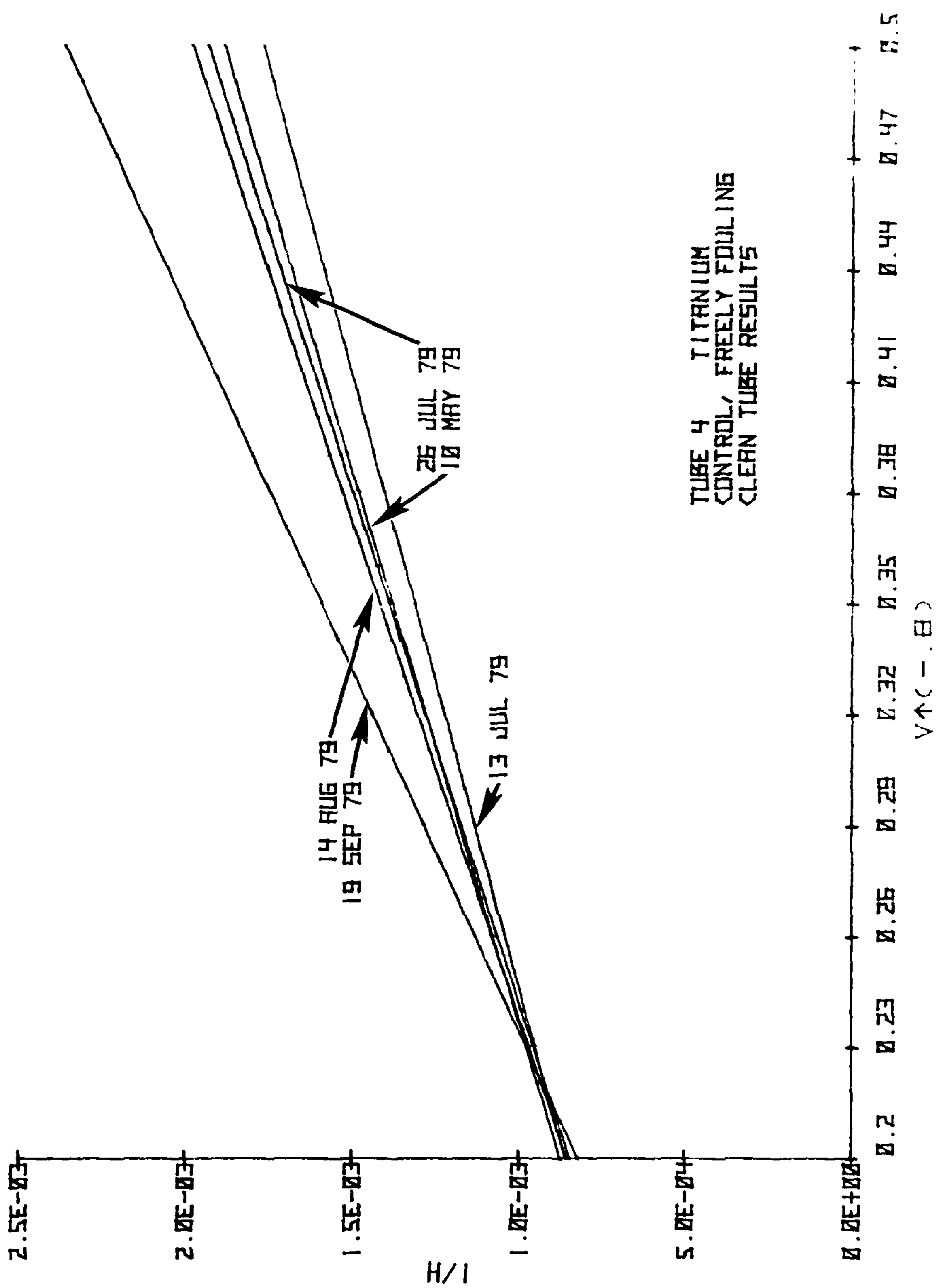

TUBE 4 TITANIUM
CONTROL, FREELY FOULING
CLEAN TUBE RESULTS
25 JUL 79
10 MAY 79
13 JUL 79
14 AUG 79
19 SEP 79
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
2.5E-03
1/H
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-12

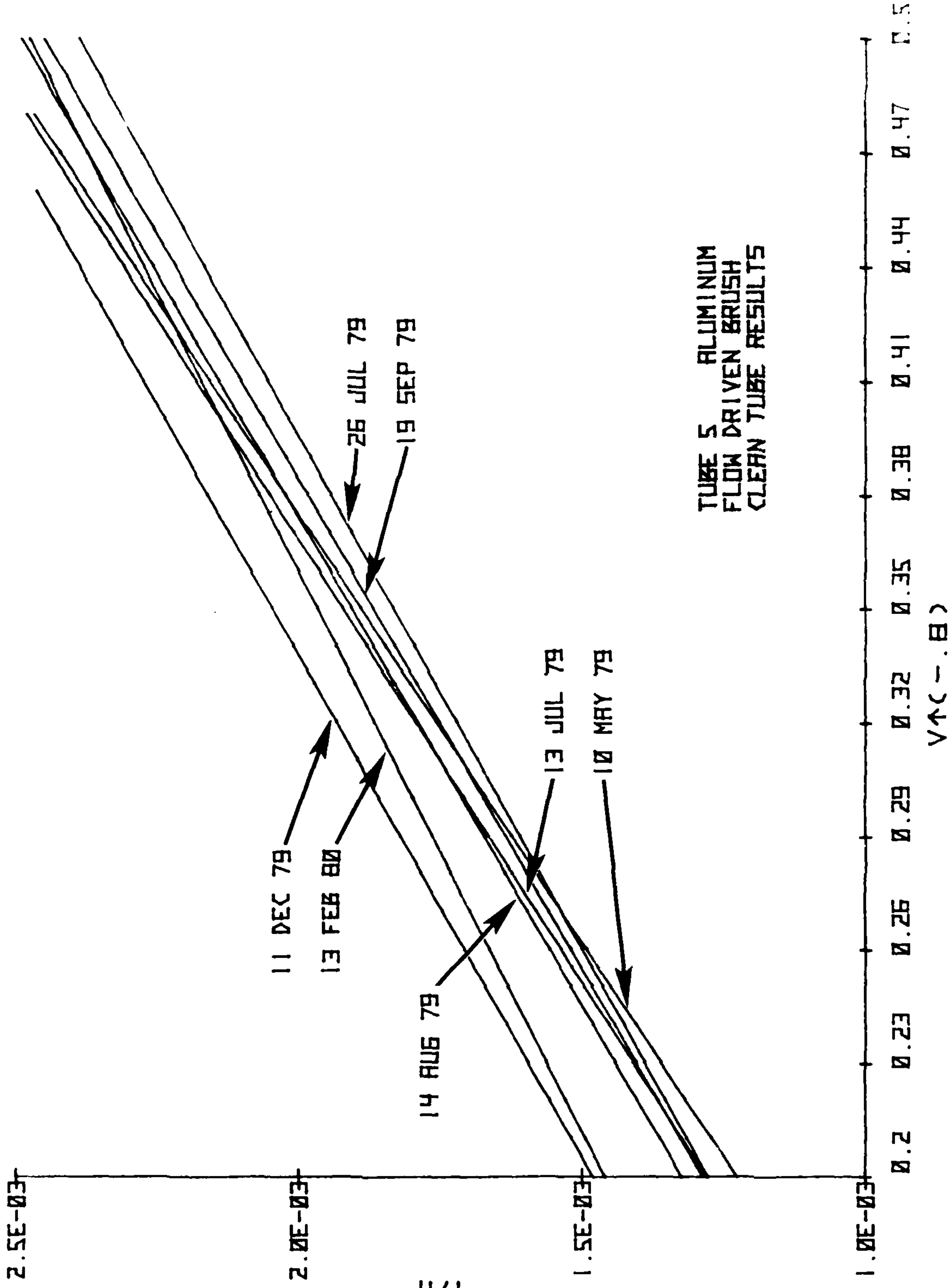

TUBE 5 ALUMINUM
FLOW DRIVEN BRUSH
CLEAN TUBE RESULTS
26 JUL 79
19 SEP 79
13 JUL 79
10 MAY 79
11 DEC 79
13 FEB 80
14 AUG 79
2.5E-03
2.0E-03
1.5E-03
1.0E-03
H/I
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-13

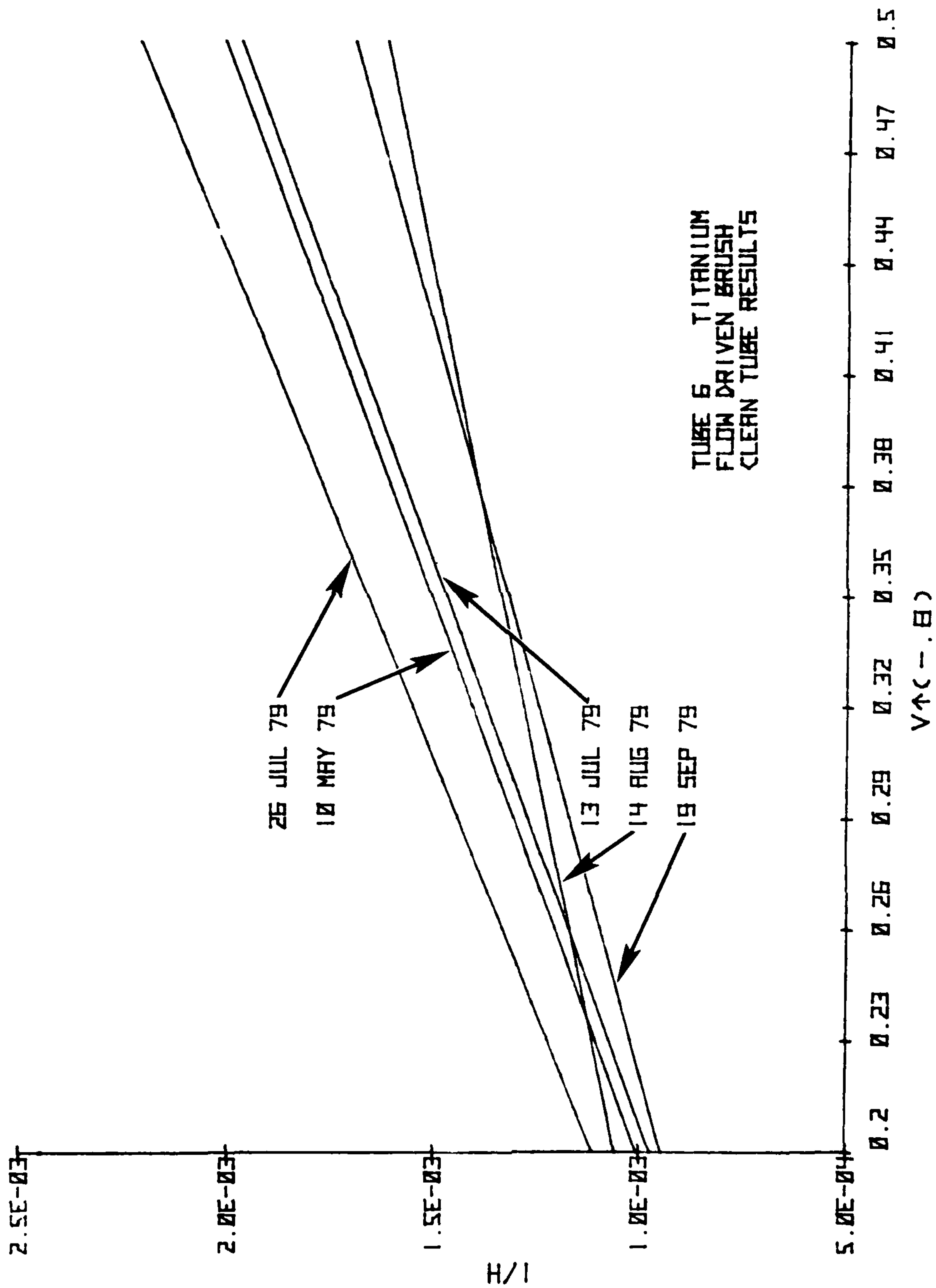

TUBE 6 TITANIUM
FLOW DRIVEN BRUSH
CLEAN TUBE RESULTS
26 JUL 79
10 MAY 79
13 JUL 79
14 AUG 79
19 SEP 79
1/H
5.0E-04
1.0E-03
1.5E-03
2.0E-03
2.5E-03
V↑(-.8)
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-14

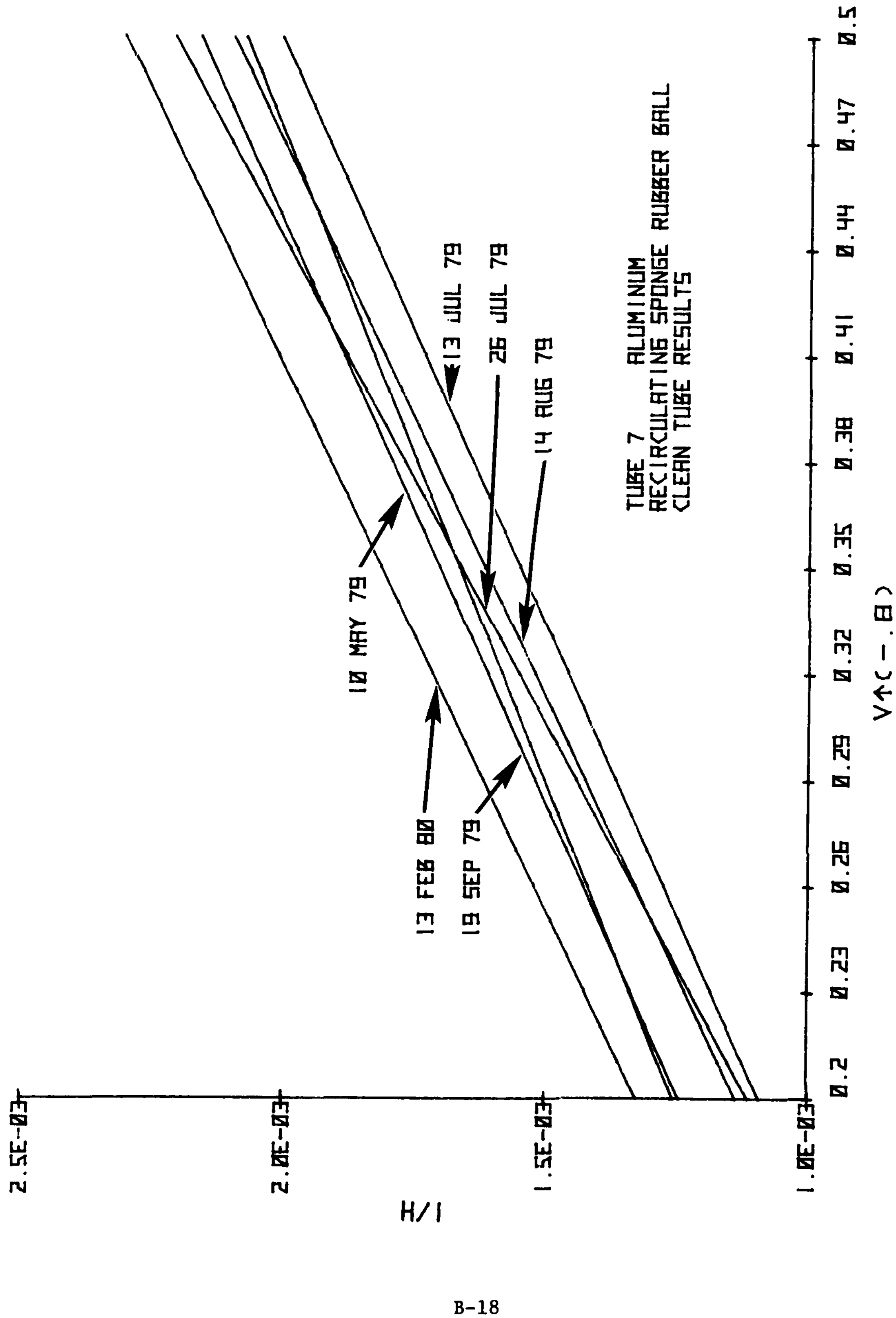

TUBE 7 ALUMINUM
RECIRCULATING SPONGE RUBBER BALL
CLEAN TUBE RESULTS
13 JUL 79
26 JUL 79
14 AUG 79
10 MAY 79
13 FEB 80
19 SEP 79
2.5E-03
2.0E-03
1.5E-03
1.0E-03
1/H
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-15

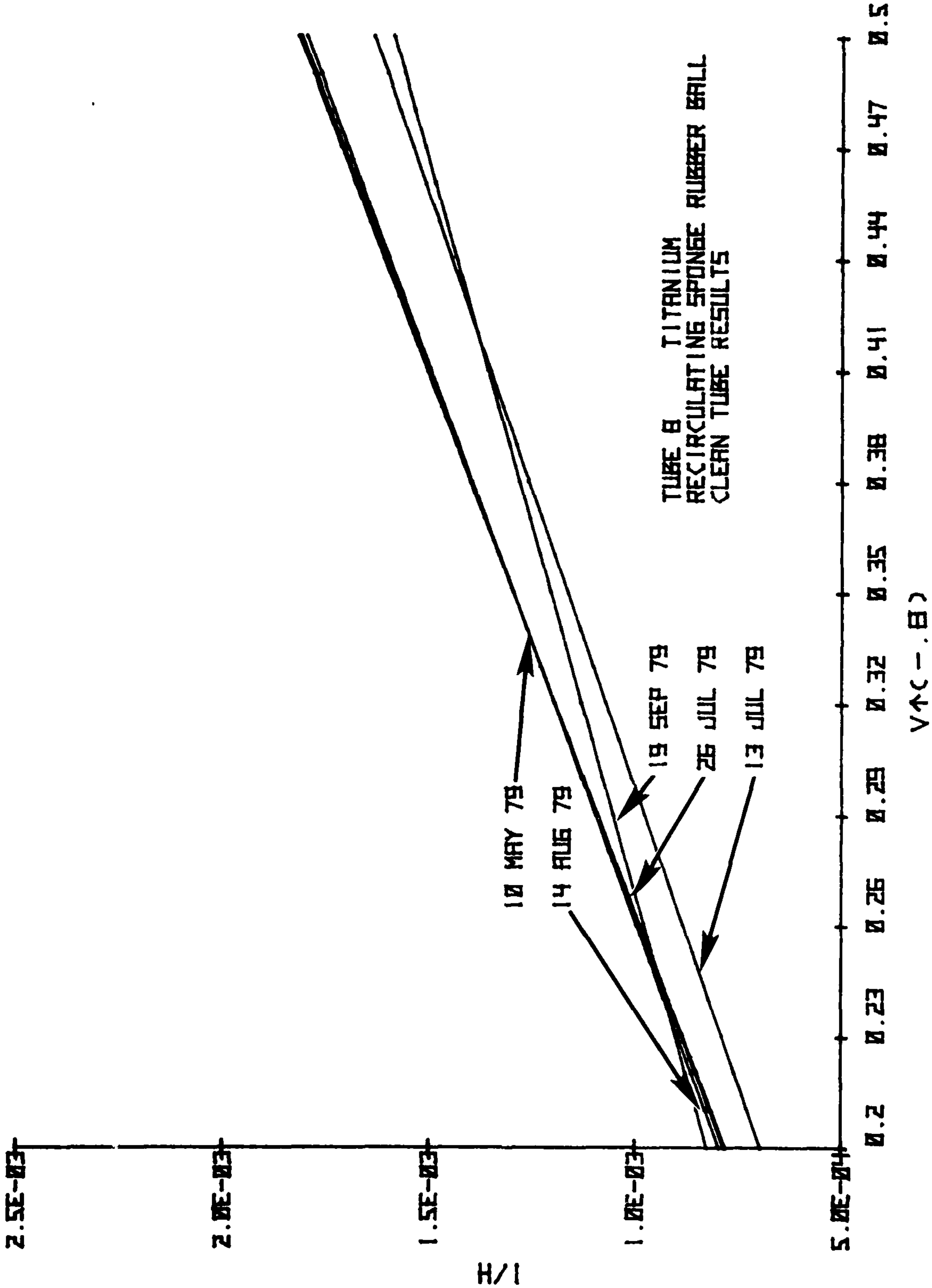

TUBE 8 TITANIUM
RECIRCULATING SPONGE RUBBER BALL
CLEAN TUBE RESULTS
10 MAY 79
14 AUG 79
19 SEP 79
26 JUL 79
13 JUL 79
V↑(-.8)
H/I
5.0E-04
1.0E-03
1.5E-03
2.0E-03
2.5E-03
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-16

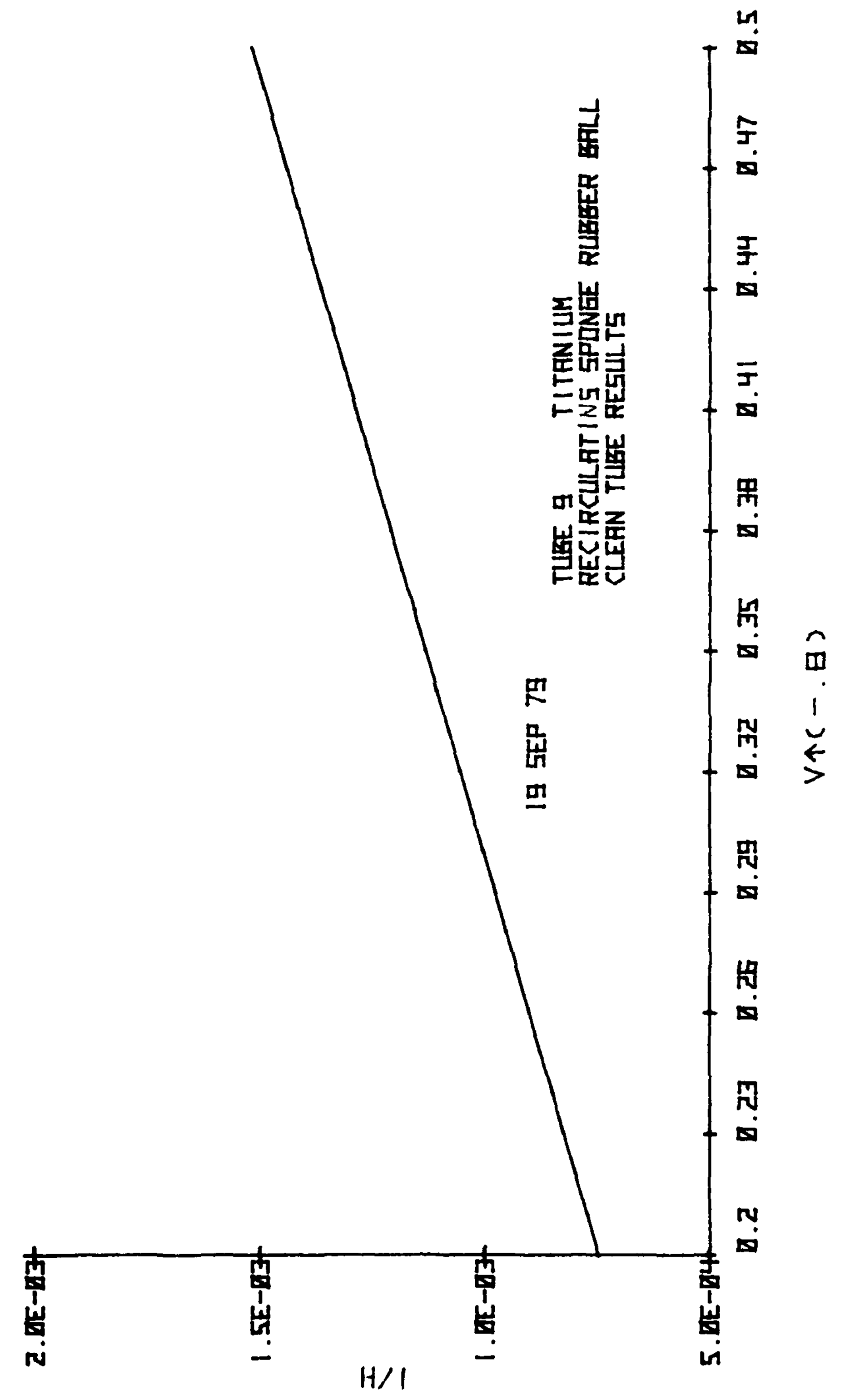

TUBE 9 TITANIUM
RECIRCULATING SPONGE RUBBER BALL
CLEAN TUBE RESULTS
19 SEP 79
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)
5.0E-04
1.0E-03
1.5E-03
2.0E-03
H/I

FIGURE B-17

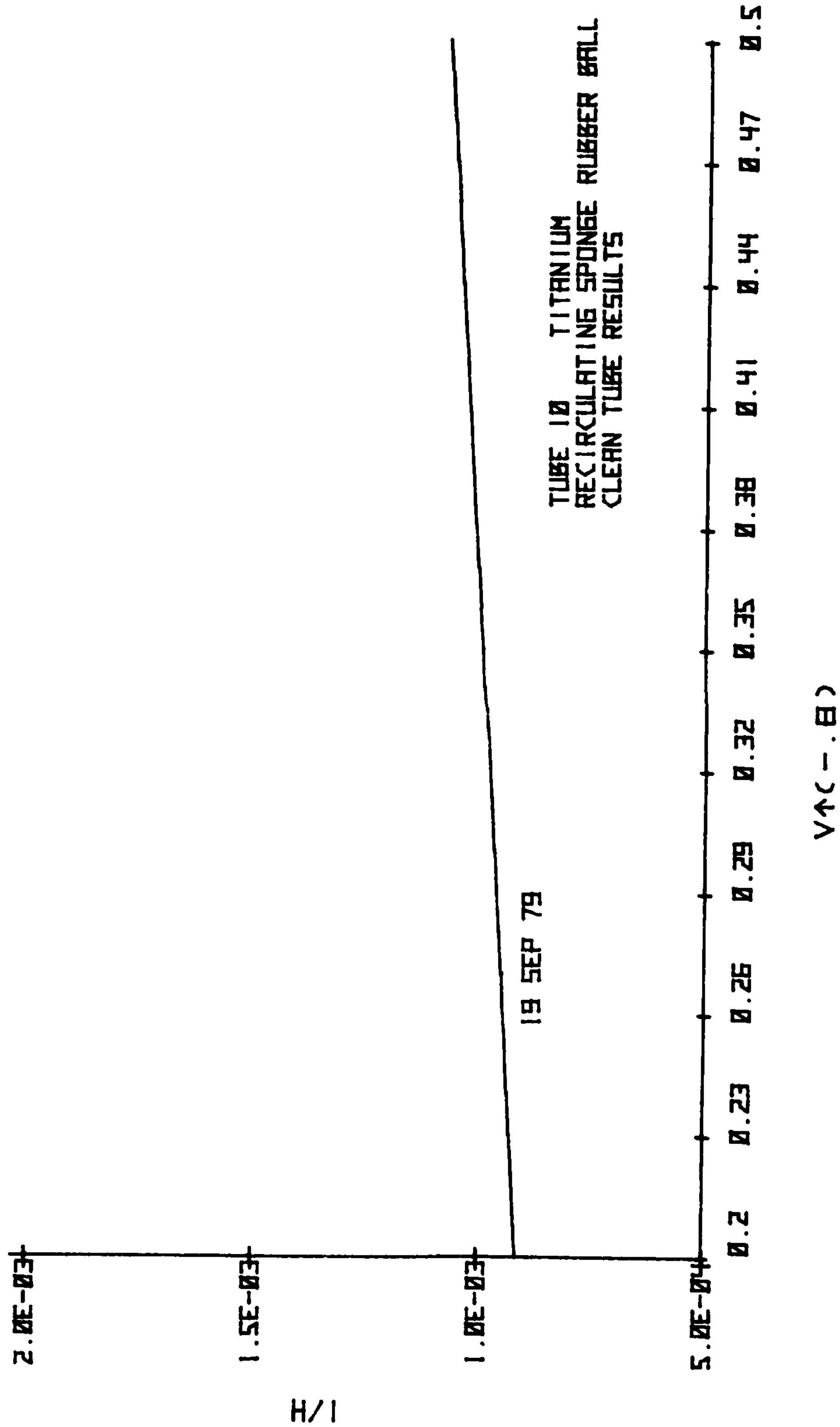

TUBE 10 TITANIUM
RECIRCULATING SPONGE RUBBER BALL
CLEAN TUBE RESULTS
19 SEP 79
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)
5.0E-04
1.0E-03
1.5E-03
2.0E-03
H/I

FIGURE B-18

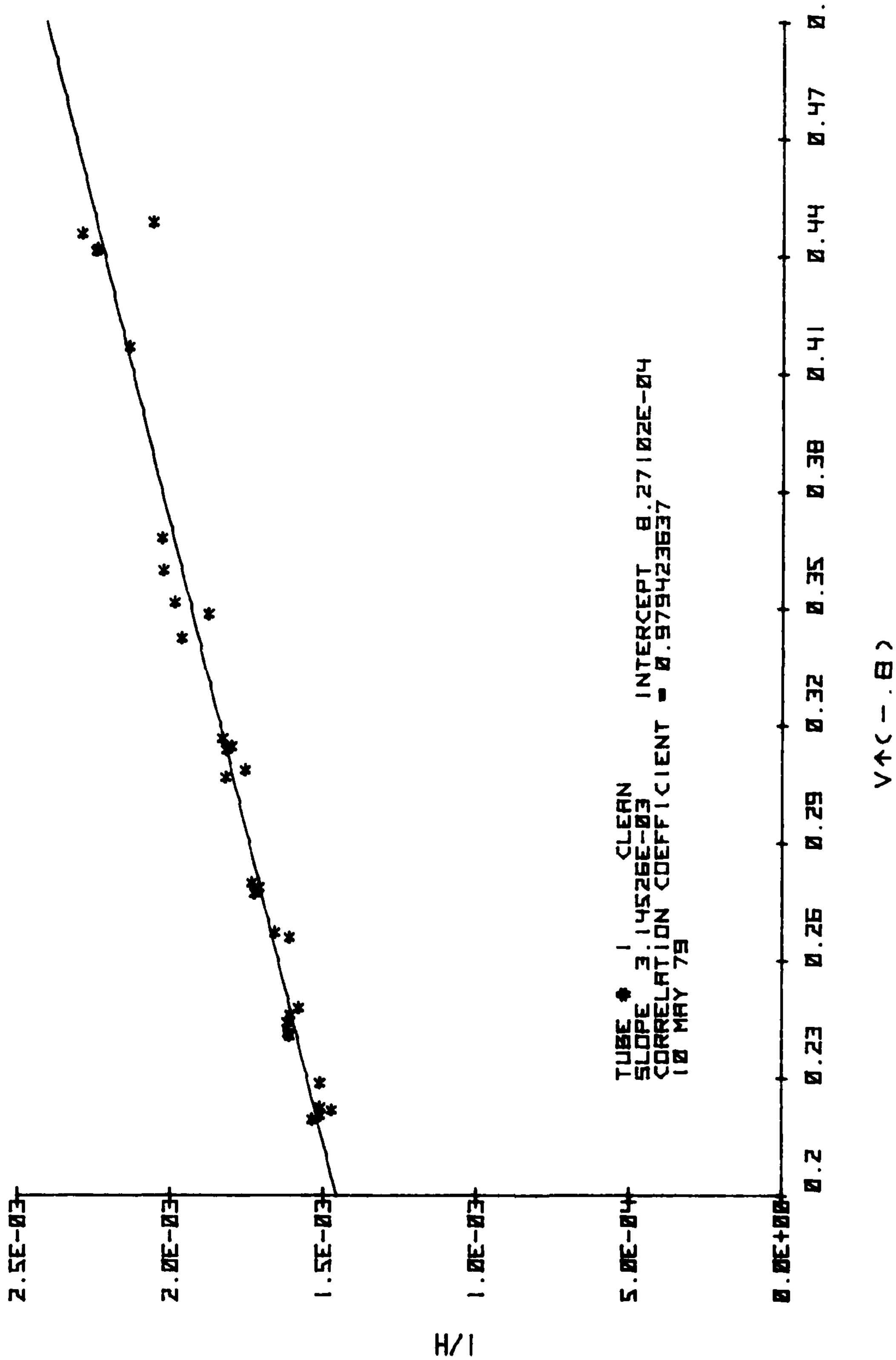

TUBE # 1 CLEAN
SLOPE 3.14526E-03 INTERCEPT 8.27102E-04
CORRELATION COEFFICIENT = 0.979423637
10 MAY 79
V↑(-.8)
H/I
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
2.5E-03

FIGURE B-19

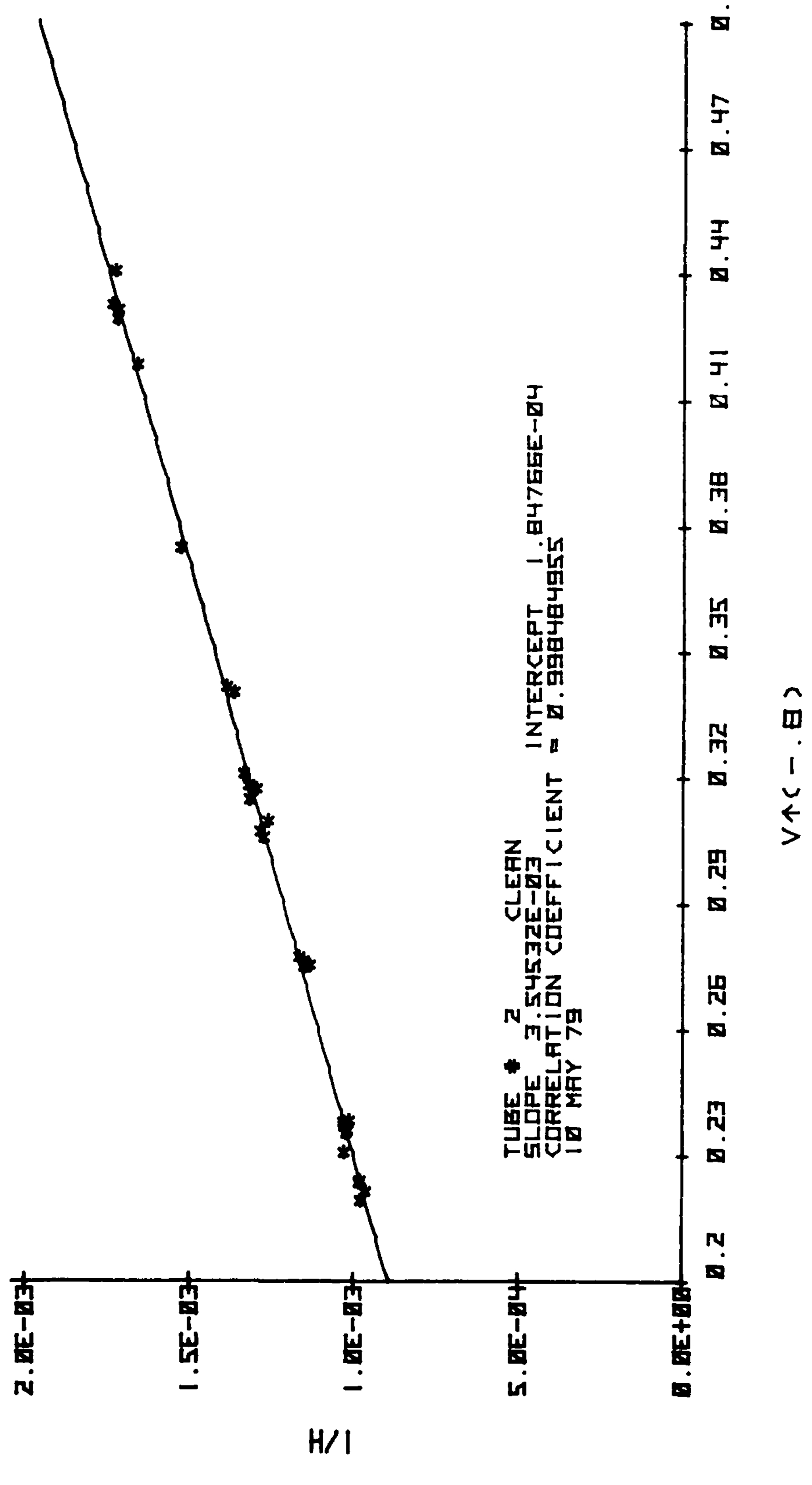

TUBE # 2 CLEAN
SLOPE 3.54532E-03 INTERCEPT 1.84766E-04
CORRELATION COEFFICIENT = 0.998484955
10 MAY 79
H/I
2.0E-03
1.5E-03
1.0E-03
5.0E-04
0.0E+00
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-20

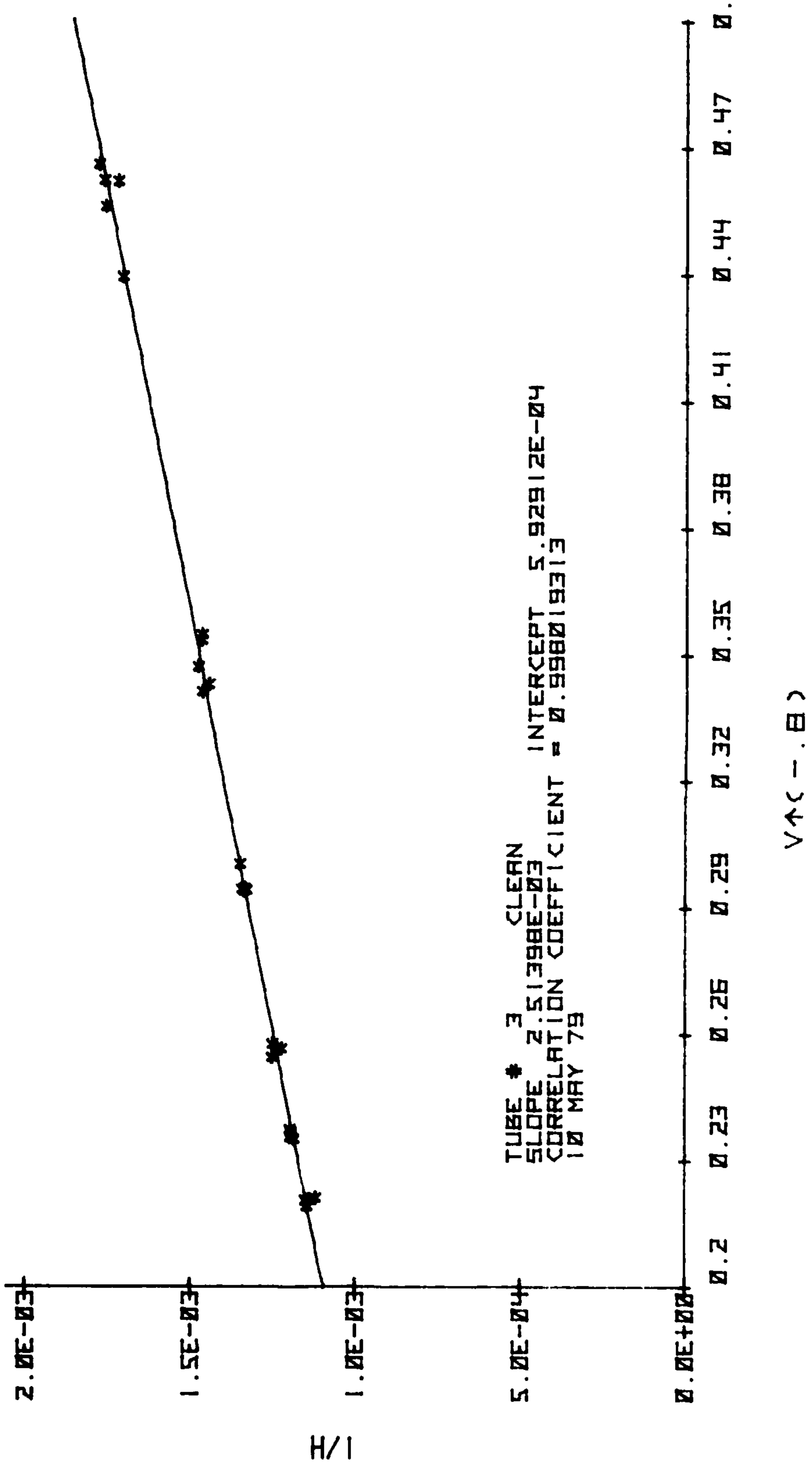

TUBE # 3 CLEAN
SLOPE 2.51398E-03 INTERCEPT 5.92912E-04
CORRELATION COEFFICIENT = 0.998019313
10 MAY 79
2.0E-03
1.5E-03
1.0E-03
5.0E-04
0.0E+00
H/I
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-21

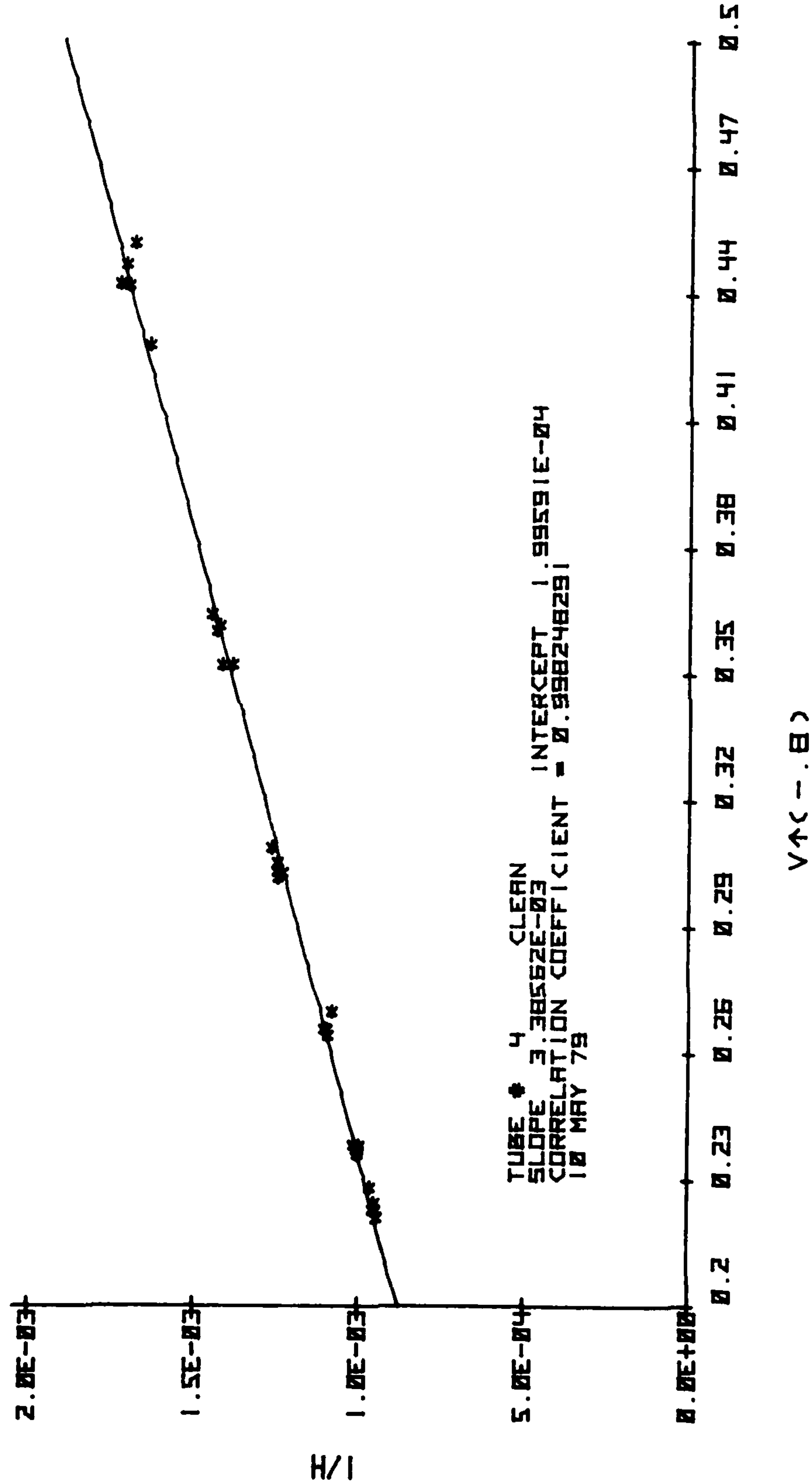

TUBE # 4 CLEAN
SLOPE 3.385626E-03 INTERCEPT 1.995916E-04
CORRELATION COEFFICIENT = 0.998248291
10 MAY 79
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
H/I
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-22

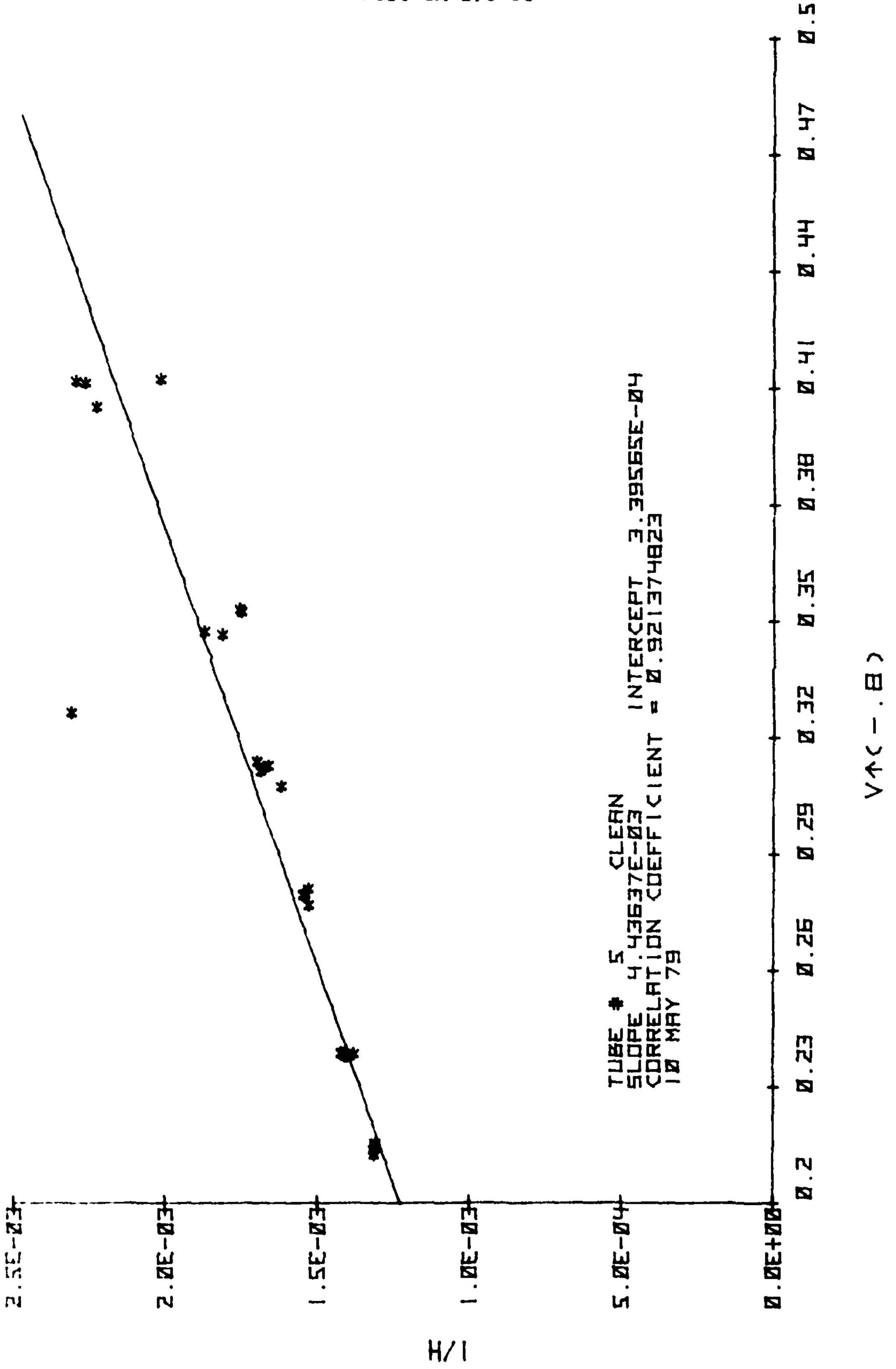

TUBE # 5 CLEAN
SLOPE 4.43637E-03 INTERCEPT 3.39565E-04
CORRELATION COEFFICIENT = 0.921374823
10 MAY 79
V↑(-.8)
H/I
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03

FIGURE B-23

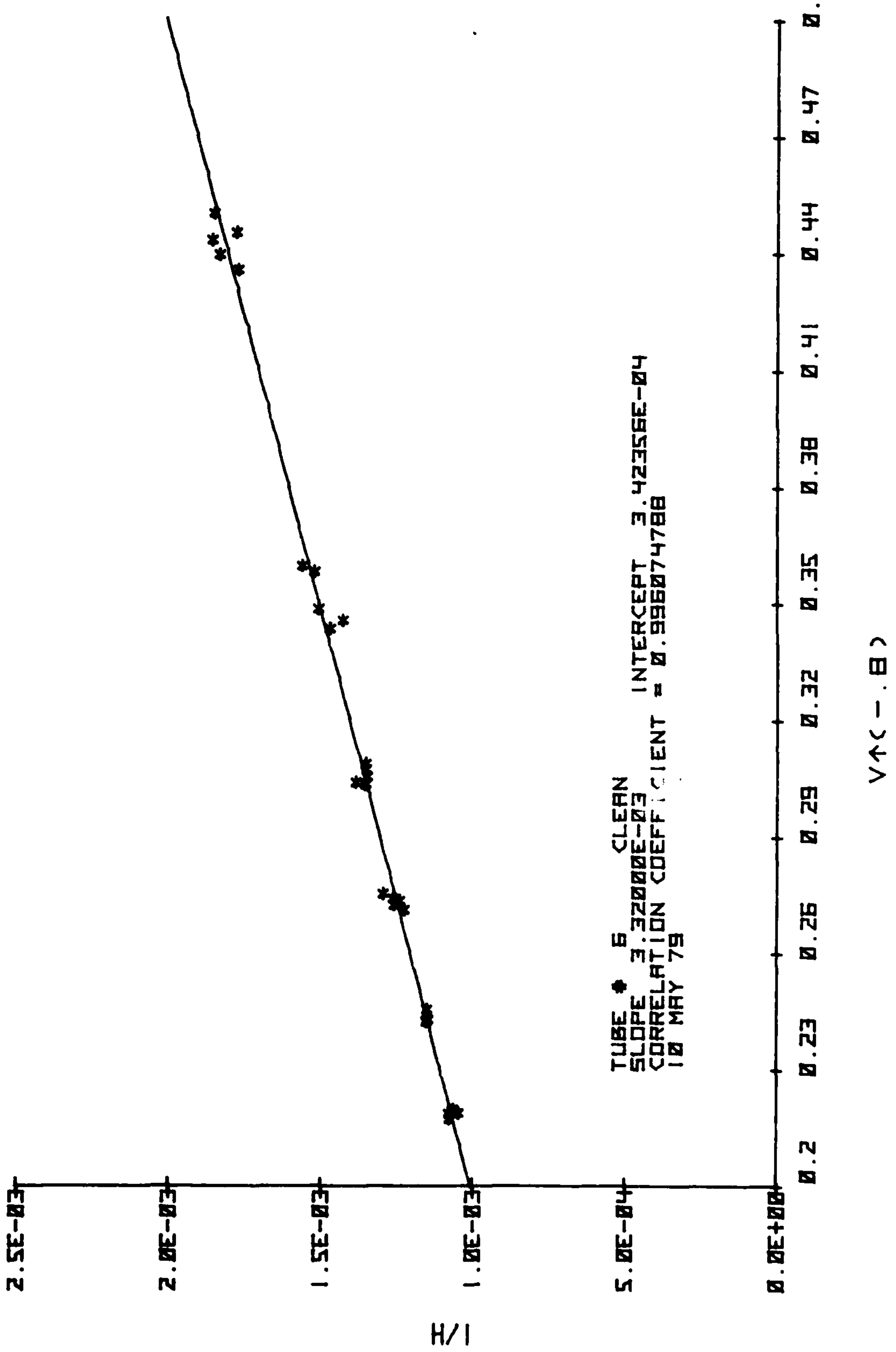

TUBE # 6 CLEAN
SLOPE 3.32000E-03 INTERCEPT 3.42356E-04
CORRELATION COEFFICIENT = 0.996074788
10 MAY 79
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
2.5E-03
H/I

FIGURE B-24

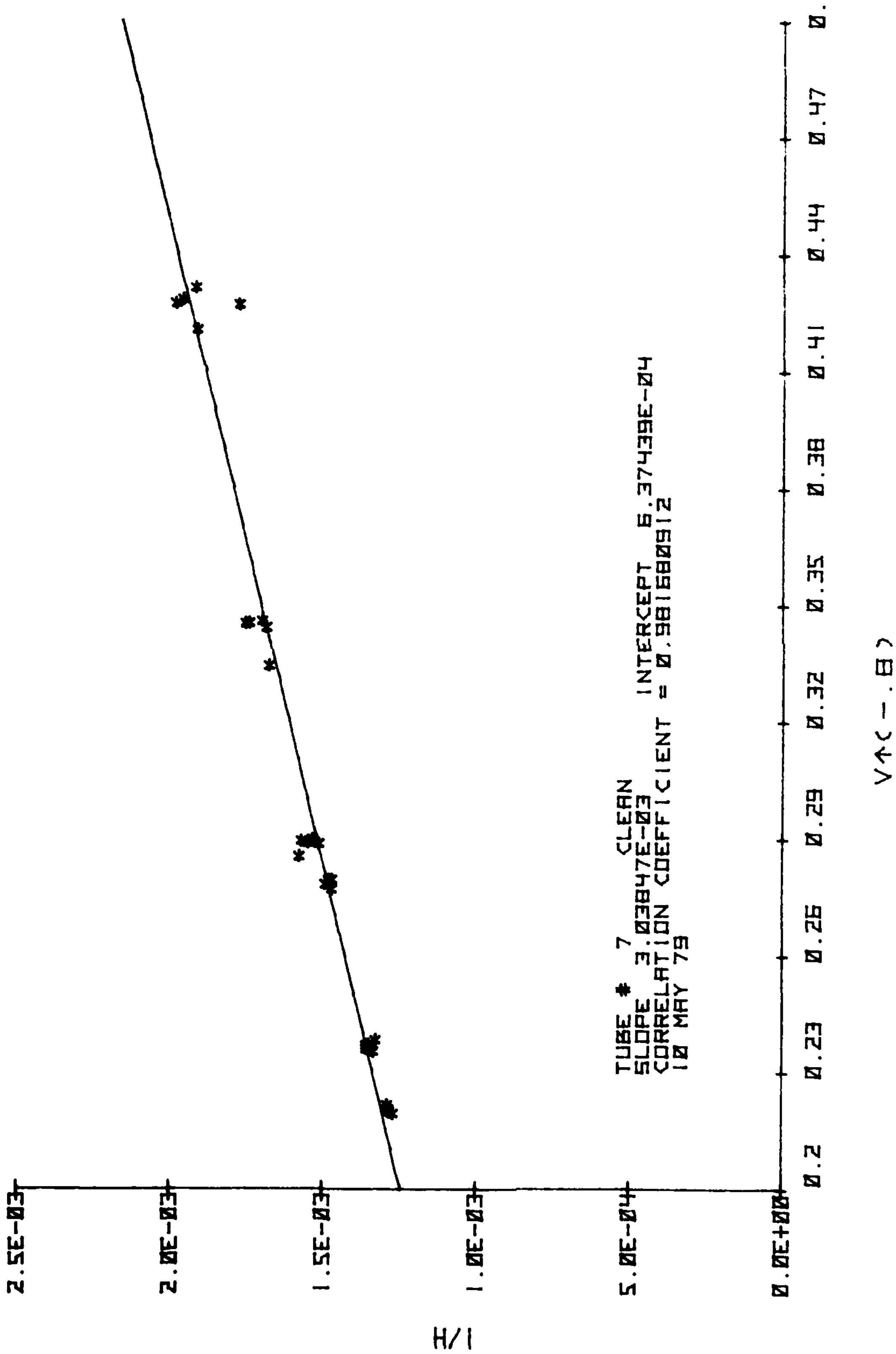

TUBE # 7 CLEAN
SLOPE 3.03847E-03 INTERCEPT 6.37439E-04
CORRELATION COEFFICIENT = 0.981680912
10 MAY 79
2.5E-03
2.0E-03
1.5E-03
1.0E-03
5.0E-04
0.0E+00
H/I
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-25

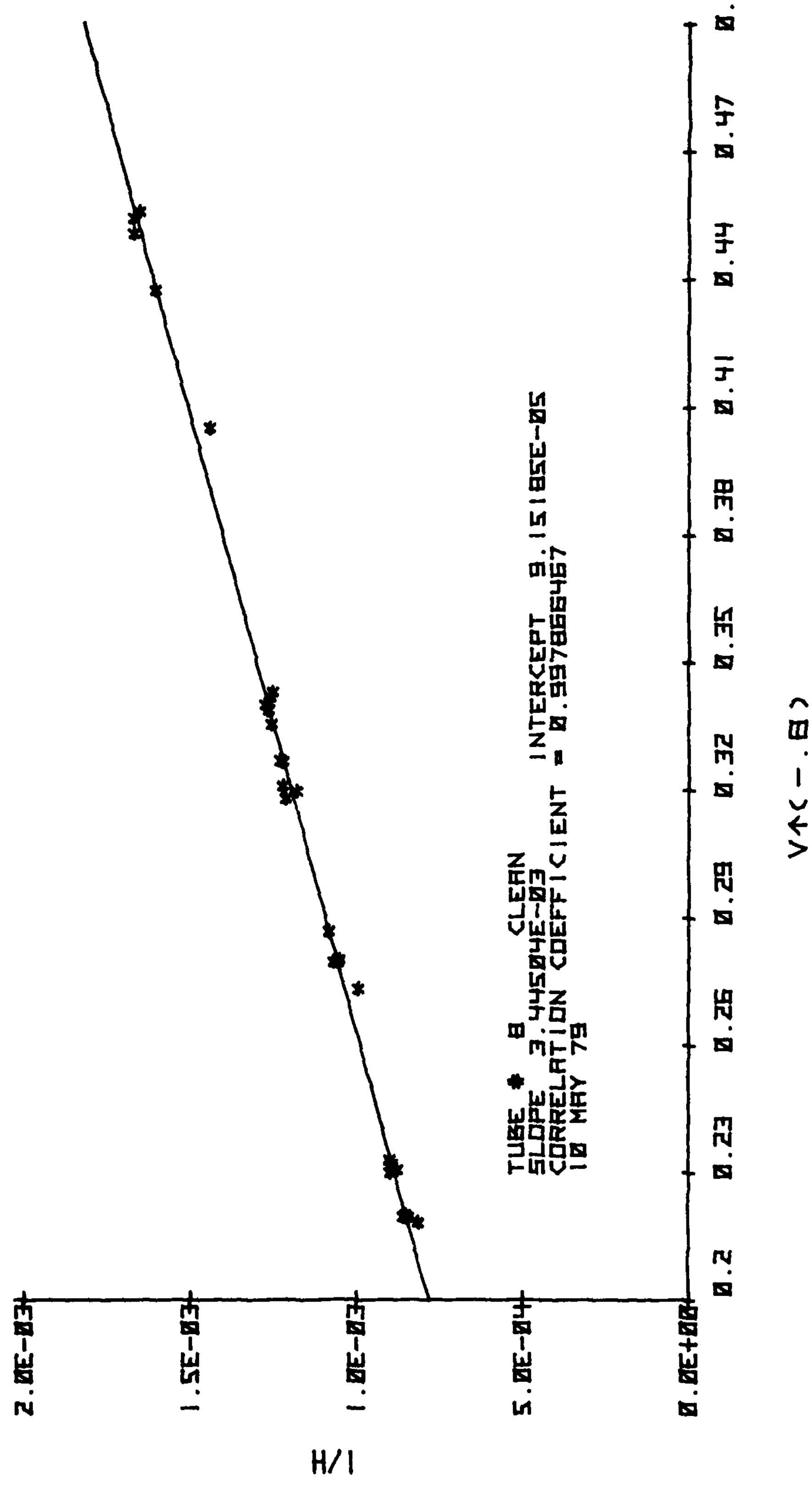

TUBE # 8 CLEAN
SLOPE 3.44504E-03 INTERCEPT 9.15185E-05
CORRELATION COEFFICIENT = 0.997866467
10 MAY 79
H/I
V↑(-.8)
2.0E-03
1.5E-03
1.0E-03
5.0E-04
0.0E+00
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-26

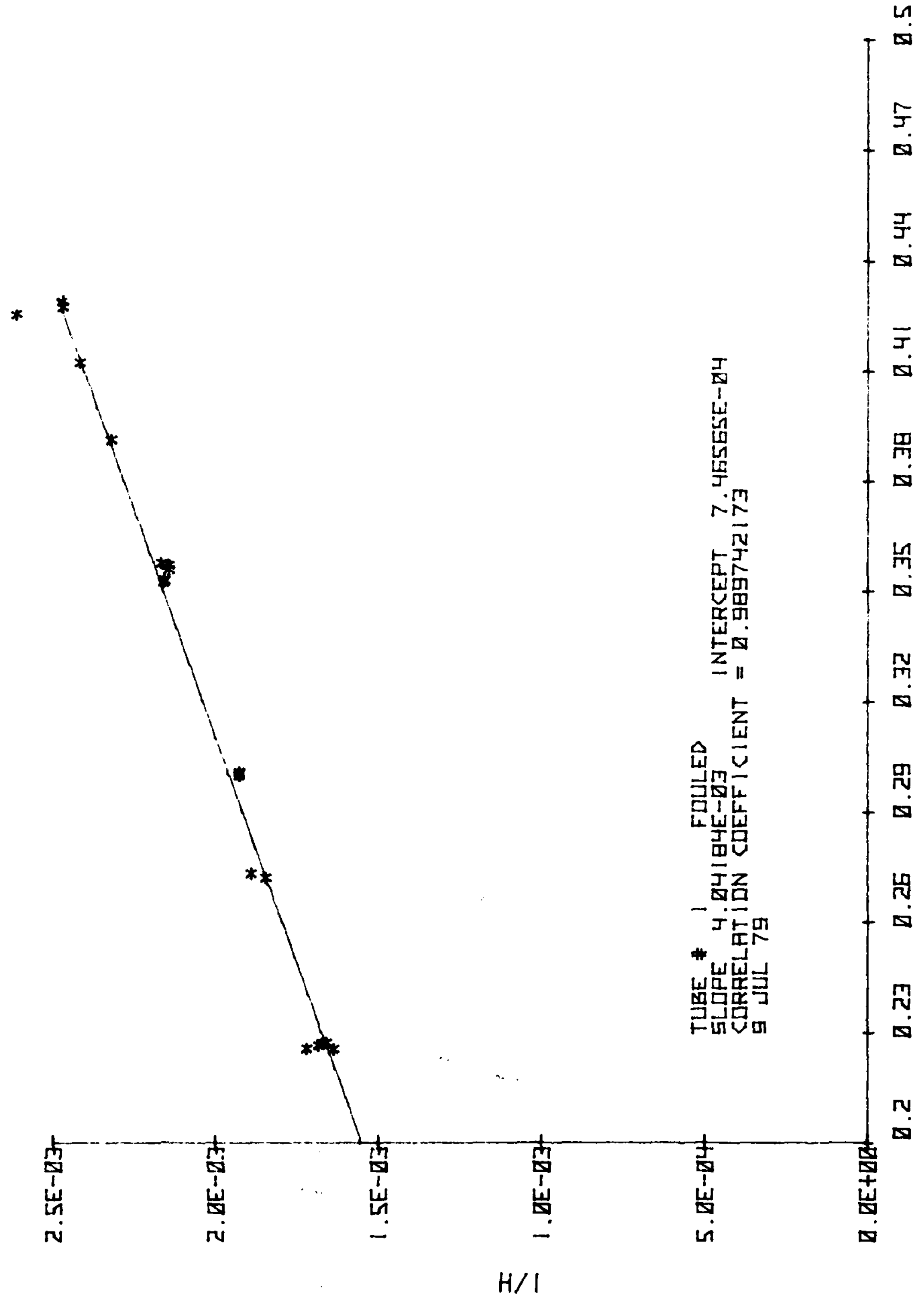

TUBE # 1 FOULED
SLOPE 4.04184E-03 INTERCEPT 7.46565E-04
CORRELATION COEFFICIENT = 0.989742173
9 JUL 79
H/I
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
2.5E-03
V↑(-.8)
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-27

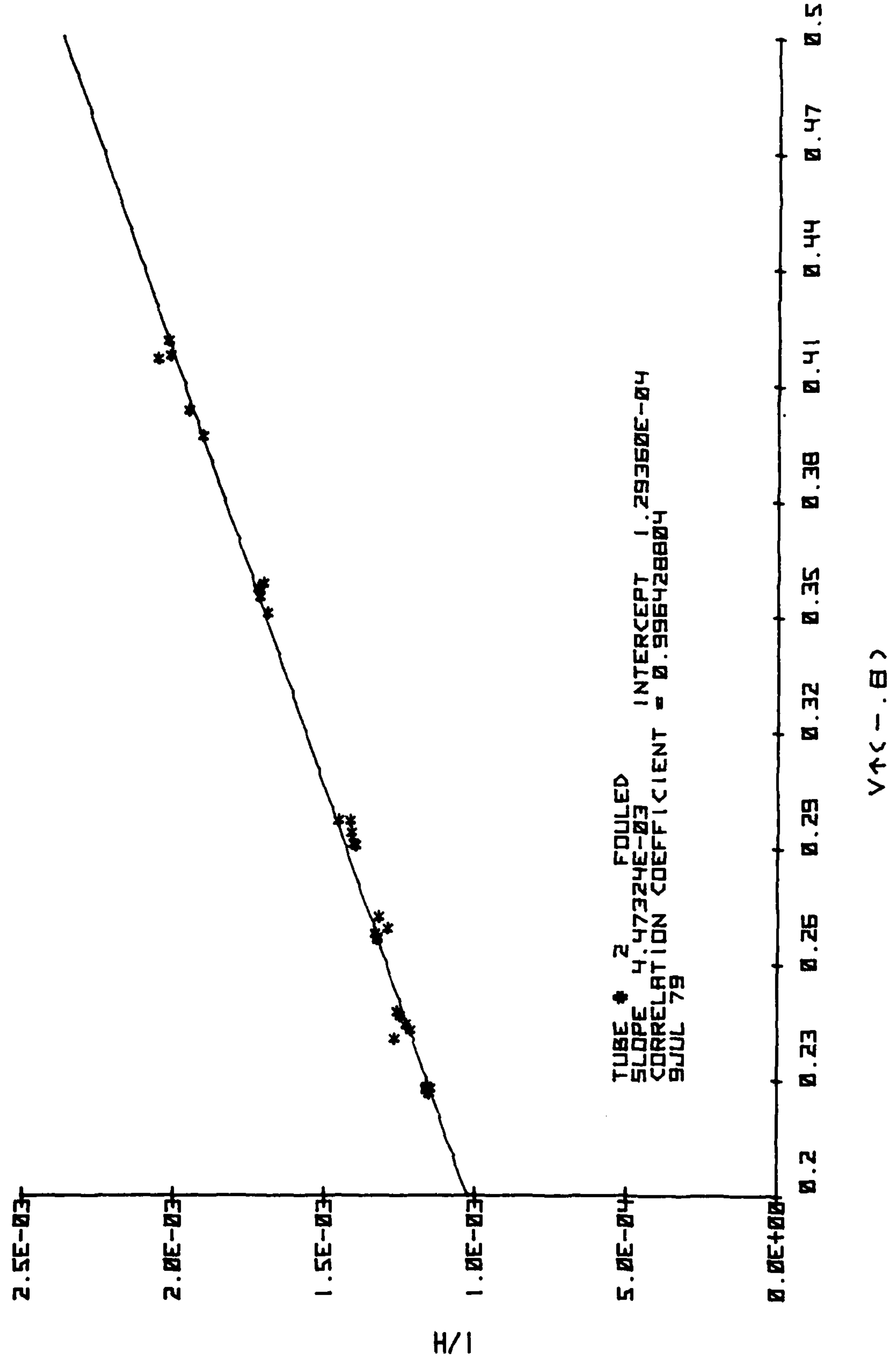

TUBE # 2 FOULED
SLOPE 4.47324E-03 INTERCEPT 1.29360E-04
CORRELATION COEFFICIENT = 0.996428804
9JUL 79
2.5E-03
2.0E-03
1.5E-03
1.0E-03
5.0E-04
0.0E+00
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)
H/I

FIGURE B-28

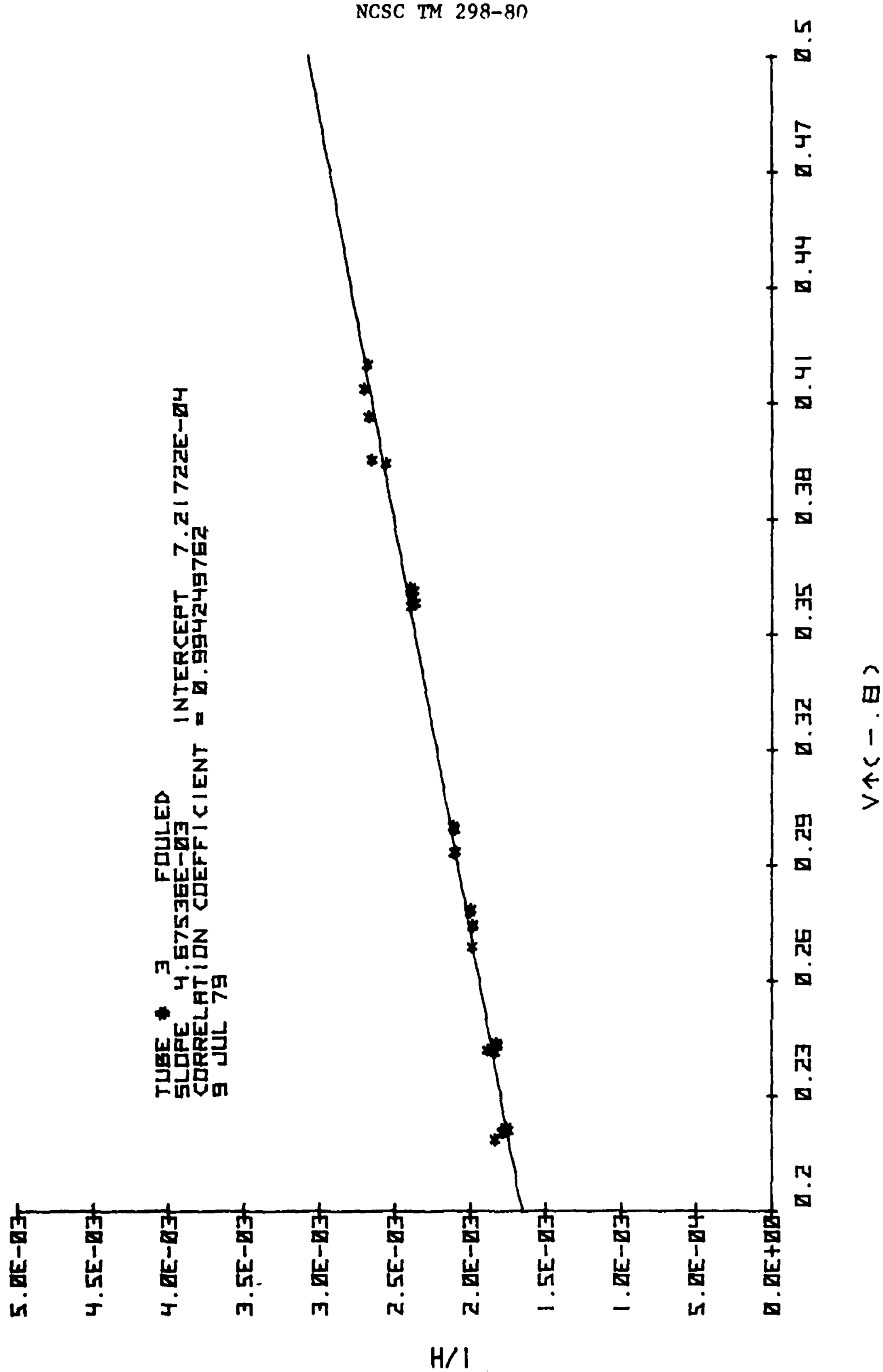

TUBE # 3 FOULED
SLOPE 4.67536E-03 INTERCEPT 7.21722E-04
CORRELATION COEFFICIENT = 0.994249762
9 JUL 79
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
2.5E-03
3.0E-03
3.5E-03
4.0E-03
4.5E-03
5.0E-03
H/I

FIGURE B-29

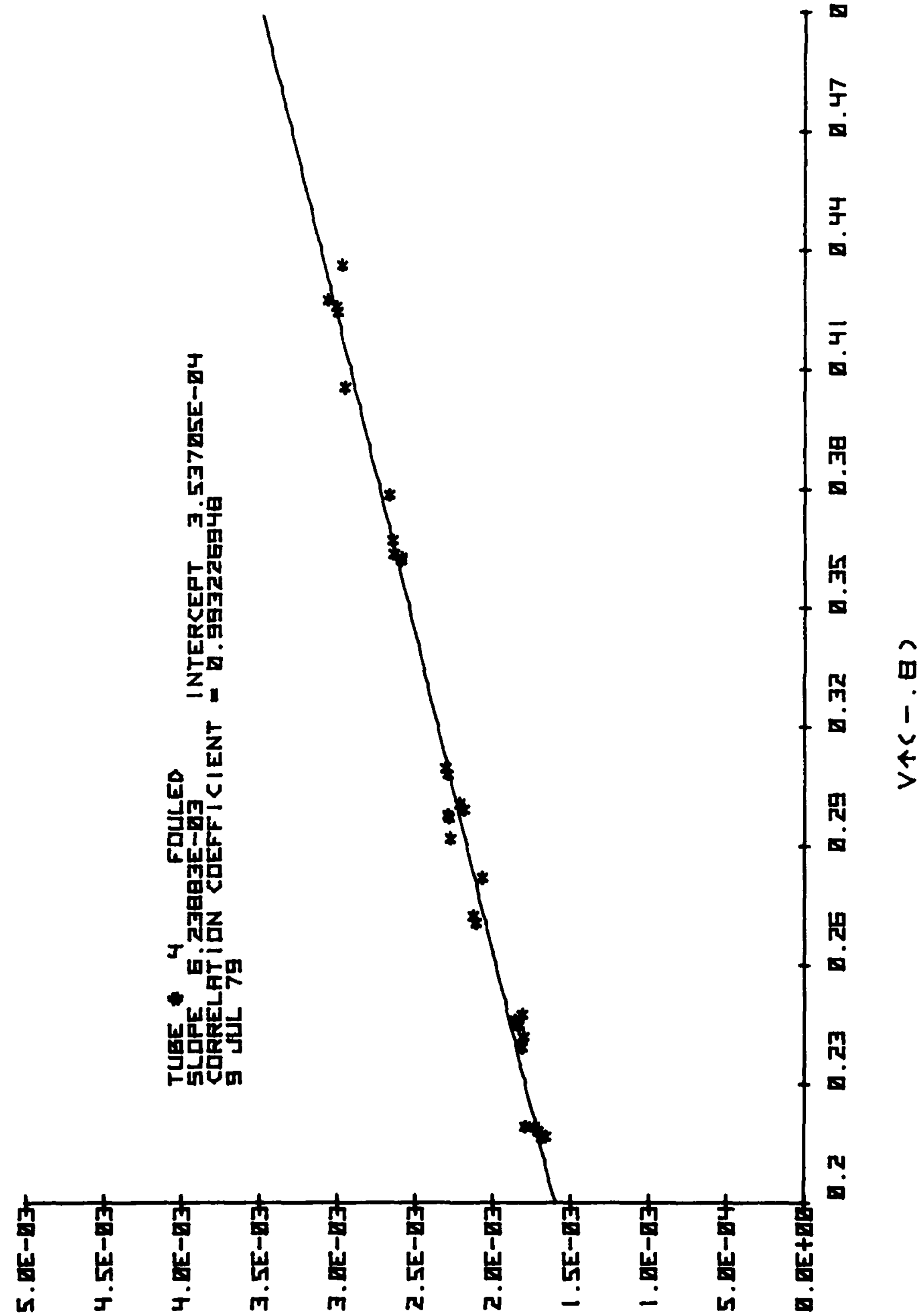

TUBE # 4 FOULED
SLOPE 6.23883E-03 INTERCEPT 3.53705E-04
CORRELATION COEFFICIENT = 0.993226948
9 JUL 79
H/I
V↑(-.8)
5.0E-03
4.5E-03
4.0E-03
3.5E-03
3.0E-03
2.5E-03
2.0E-03
1.5E-03
1.0E-03
5.0E-04
0.0E+00
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-30

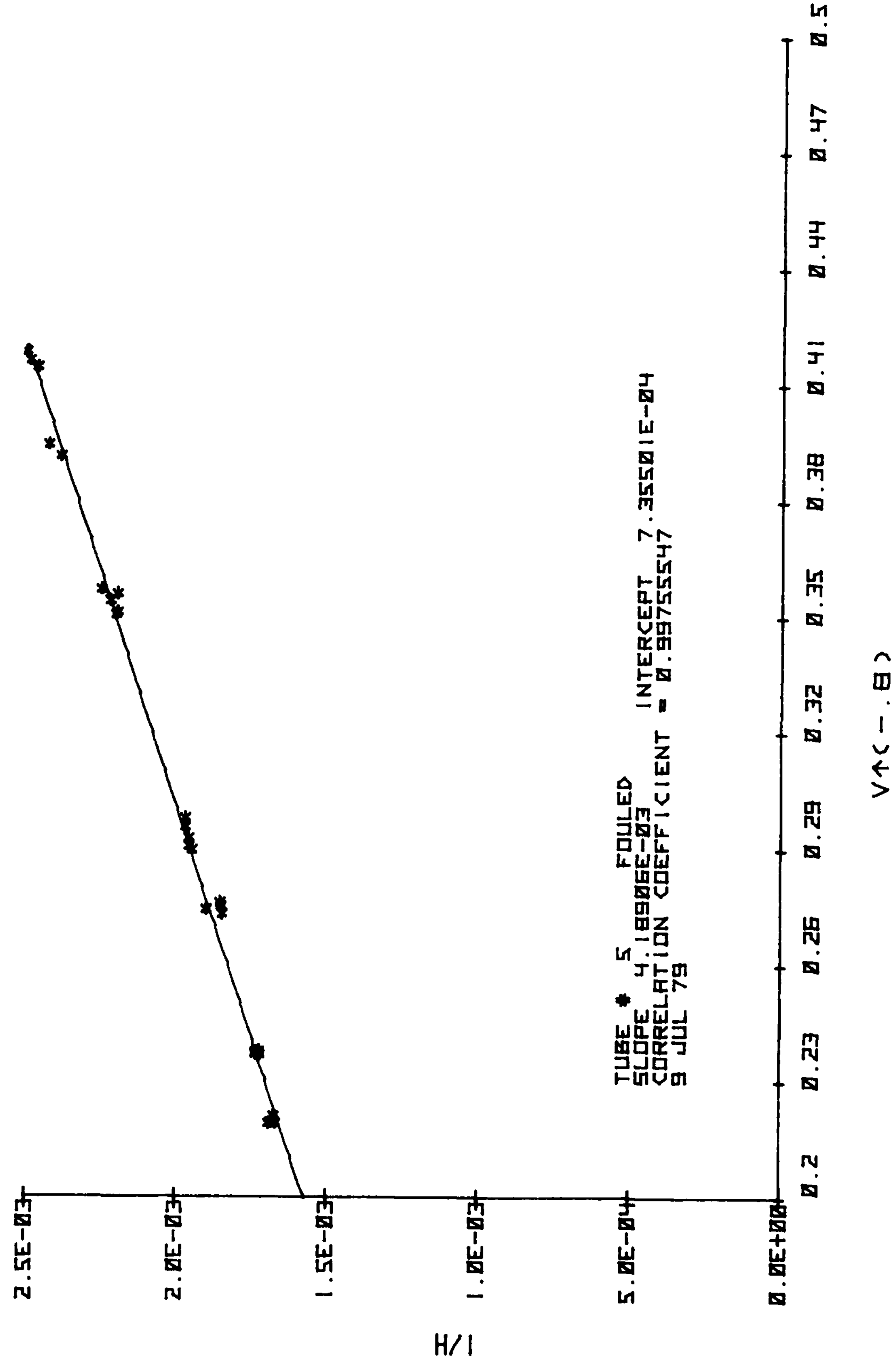

TUBE # 5 FOULED
SLOPE 4.18906E-03 INTERCEPT 7.35501E-04
CORRELATION COEFFICIENT = 0.99755547
9 JUL 79
2.5E-03
2.0E-03
1.5E-03
1.0E-03
5.0E-04
0.0E+00
H/I
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-31

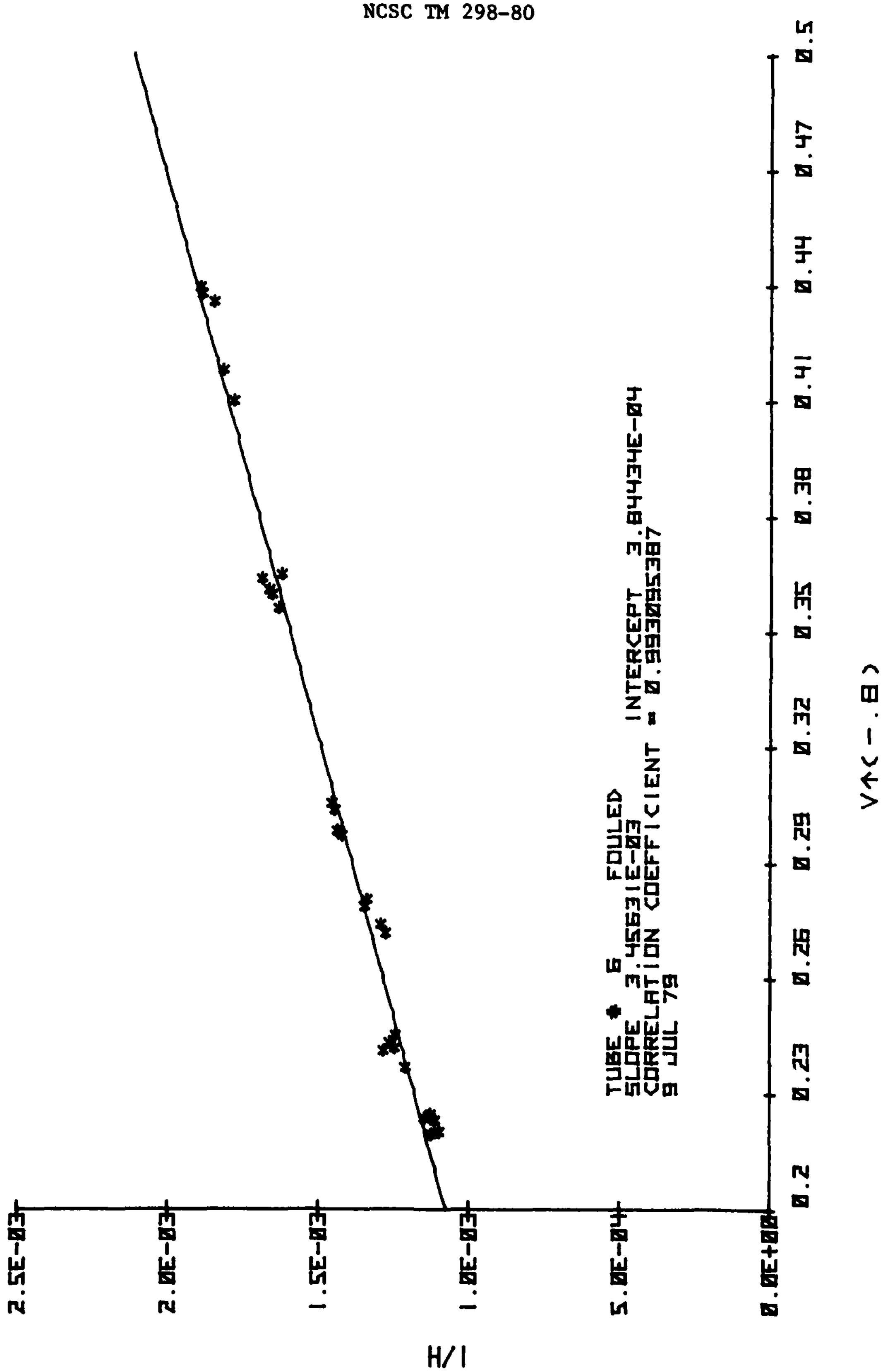

TUBE # 6 FOULED
SLOPE 3.45631E-03 INTERCEPT 3.84434E-04
CORRELATION COEFFICIENT = 0.993095387
9 JUL 79
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
2.5E-03
H/I

FIGURE B-32

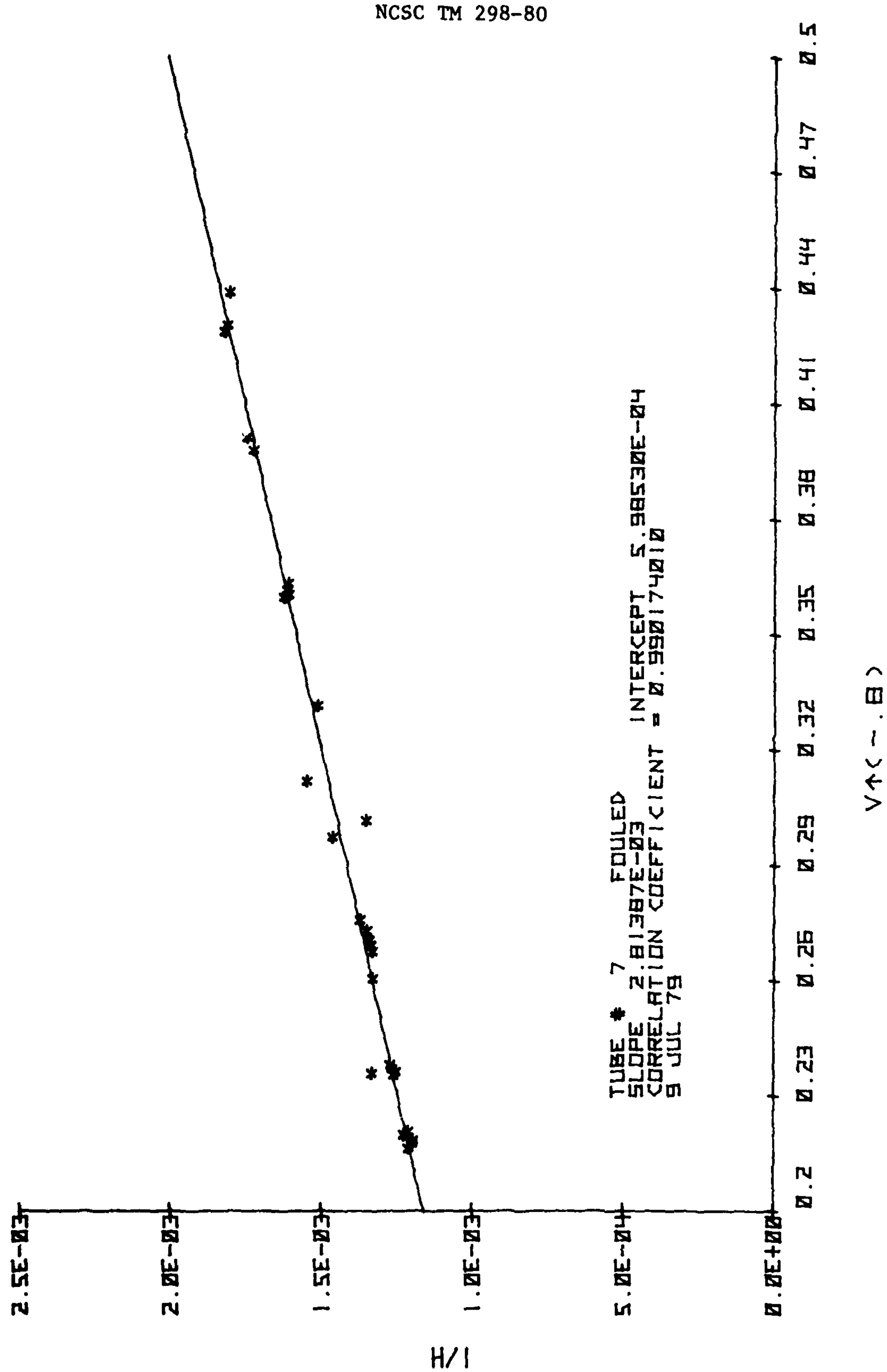

TUBE # 7 FOULED
SLOPE 2.81387E-03 INTERCEPT 5.98530E-04
CORRELATION COEFFICIENT = 0.990174010
9 JUL 79
H/I
V↑(-.8)
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
2.5E-03
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-33

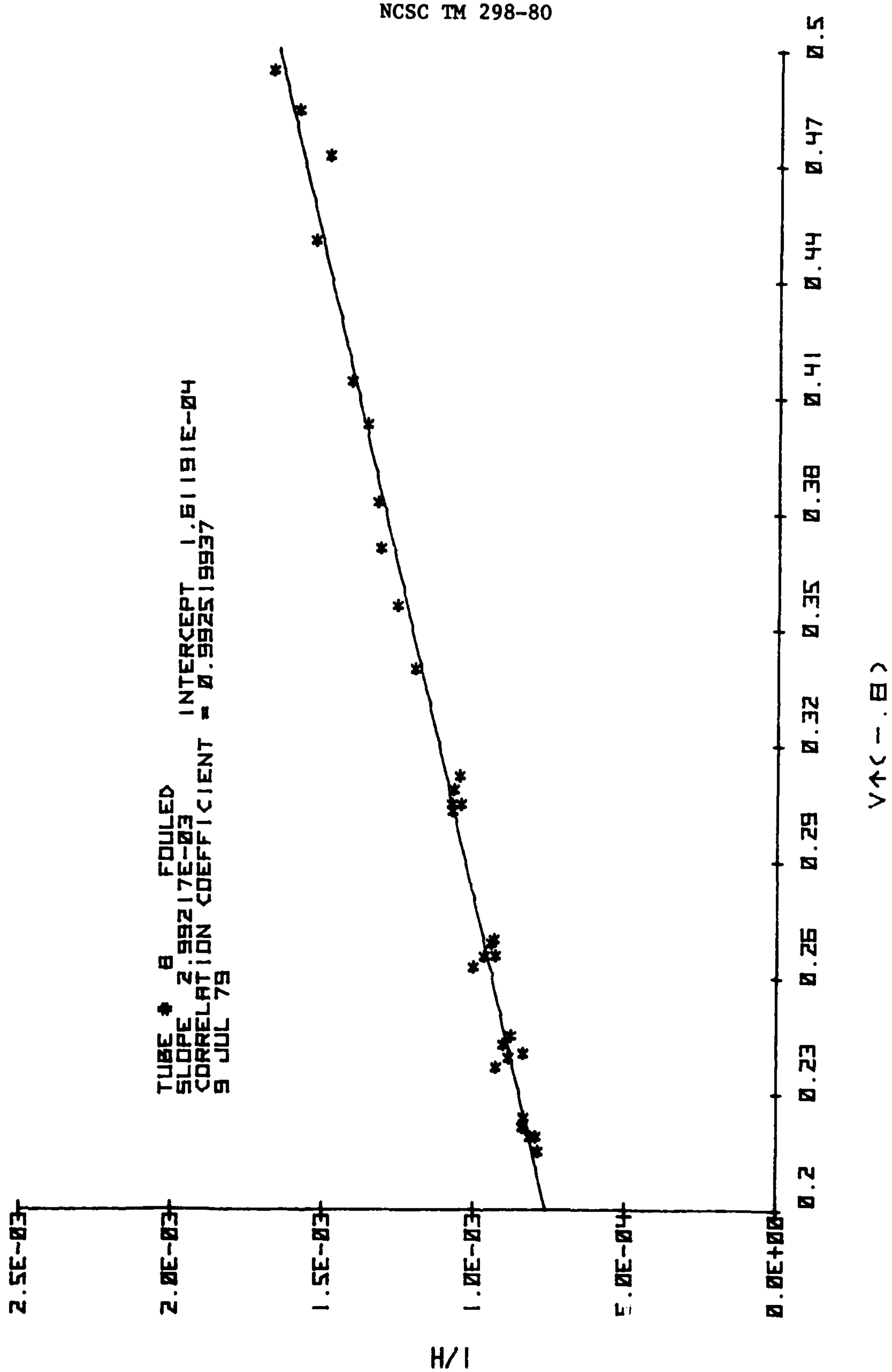

TUBE # 8 FOULED
SLOPE 2.99217E-03 INTERCEPT 1.61191E-04
CORRELATION COEFFICIENT = 0.992519937
9 JUL 79
H/I
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
2.5E-03
V↑(-.8)
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-34

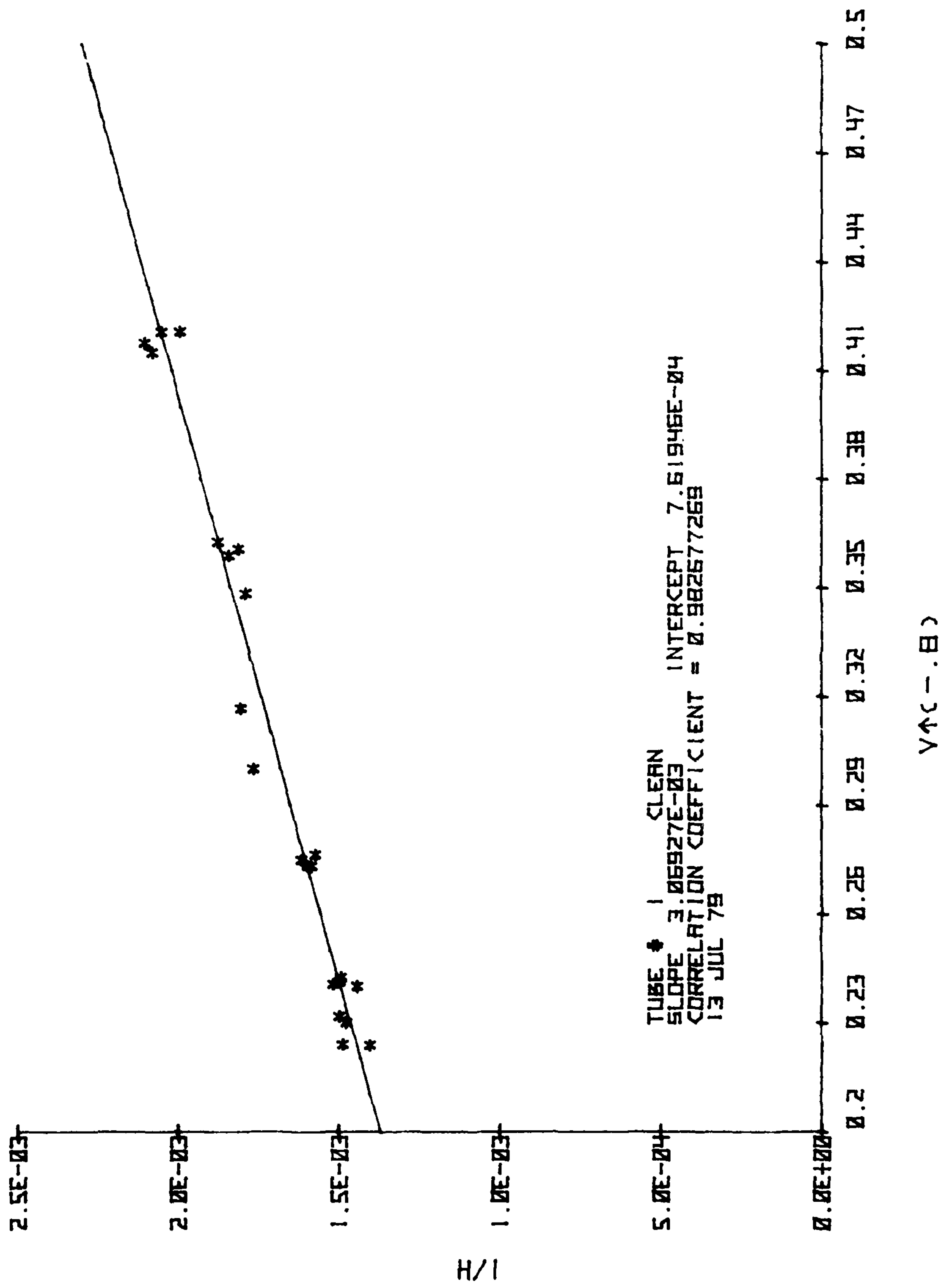

TUBE # 1 CLEAN
SLOPE 3.05927E-03 INTERCEPT 7.61946E-04
CORRELATION COEFFICIENT = 0.982677269
13 JUL 79
H/I
2.5E-03
2.0E-03
1.5E-03
1.0E-03
5.0E-04
0.0E+00
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-35

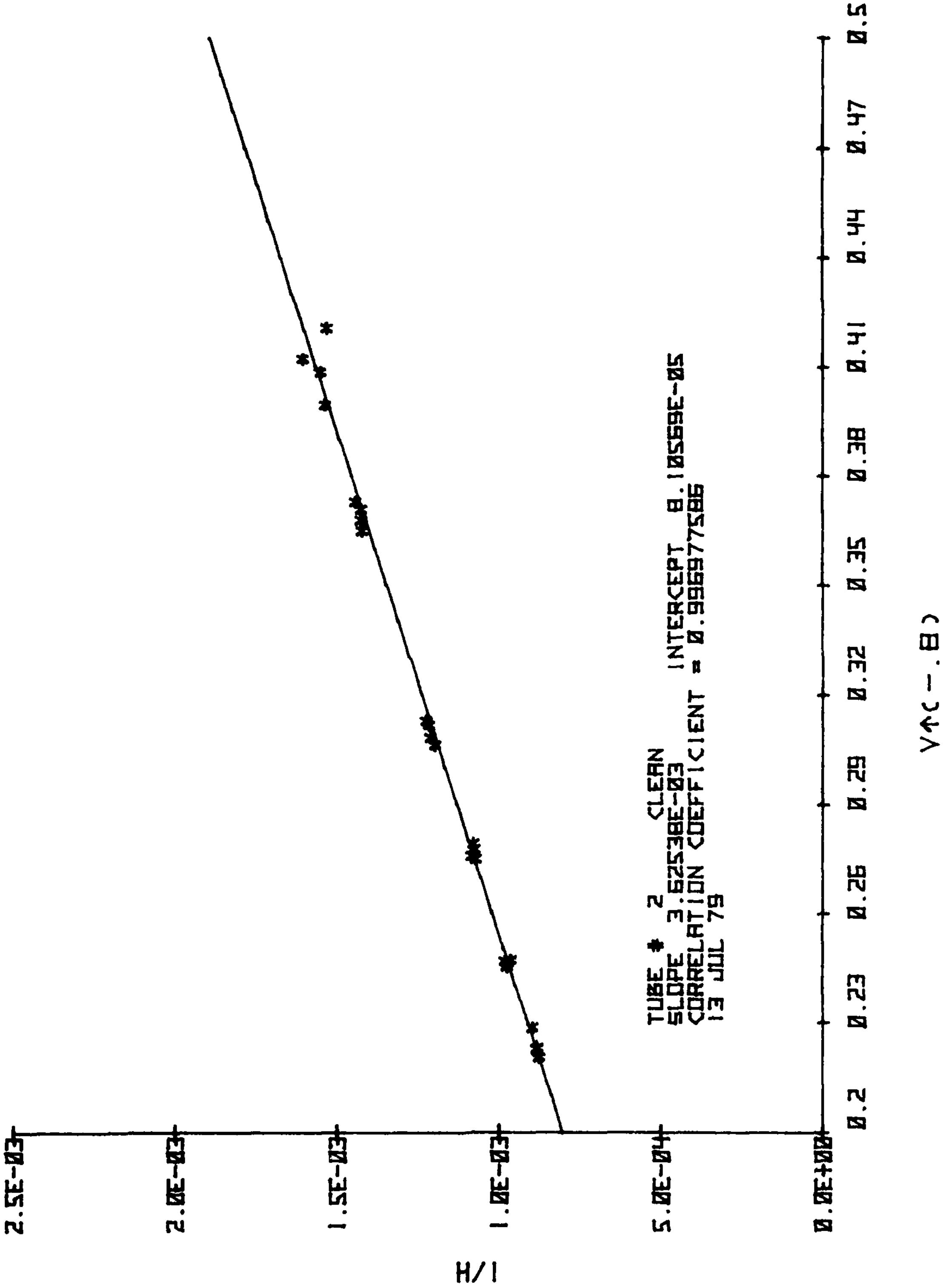

TUBE # 2 CLEAN
SLOPE 3.625388E-03 INTERCEPT 8.10559E-05
CORRELATION COEFFICIENT = 0.996977586
13 JUL 79
H/I
2.5E-03
2.0E-03
1.5E-03
1.0E-03
5.0E-04
0.0E+00
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V^(-.8)

FIGURE B-36

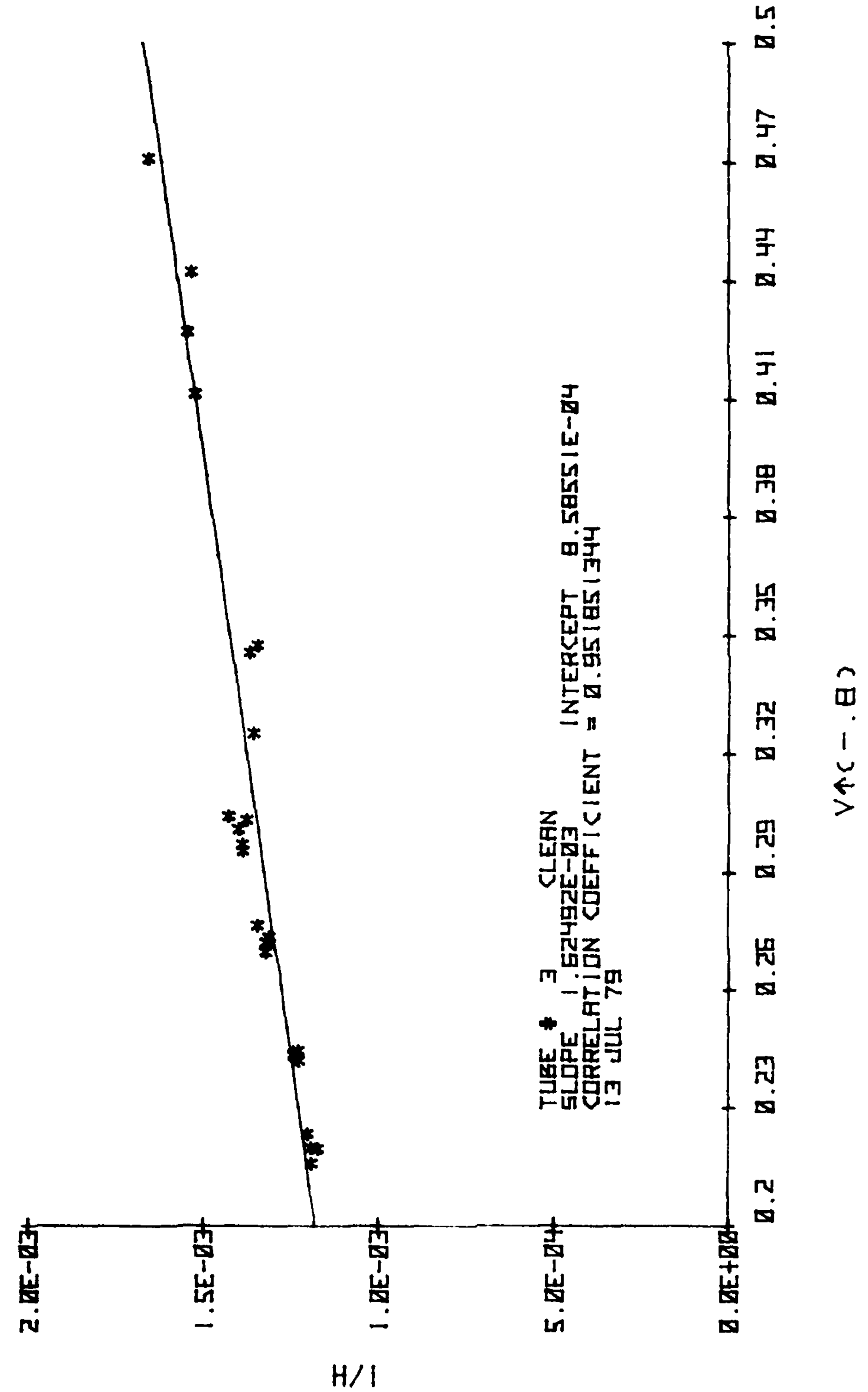

TUBE # 3 CLEAN
SLOPE 1.62492E-03 INTERCEPT 8.58551E-04
CORRELATION COEFFICIENT = 0.951851344
13 JUL 79
H/I
2.0E-03
1.5E-03
1.0E-03
5.0E-04
0.0E+00
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-37

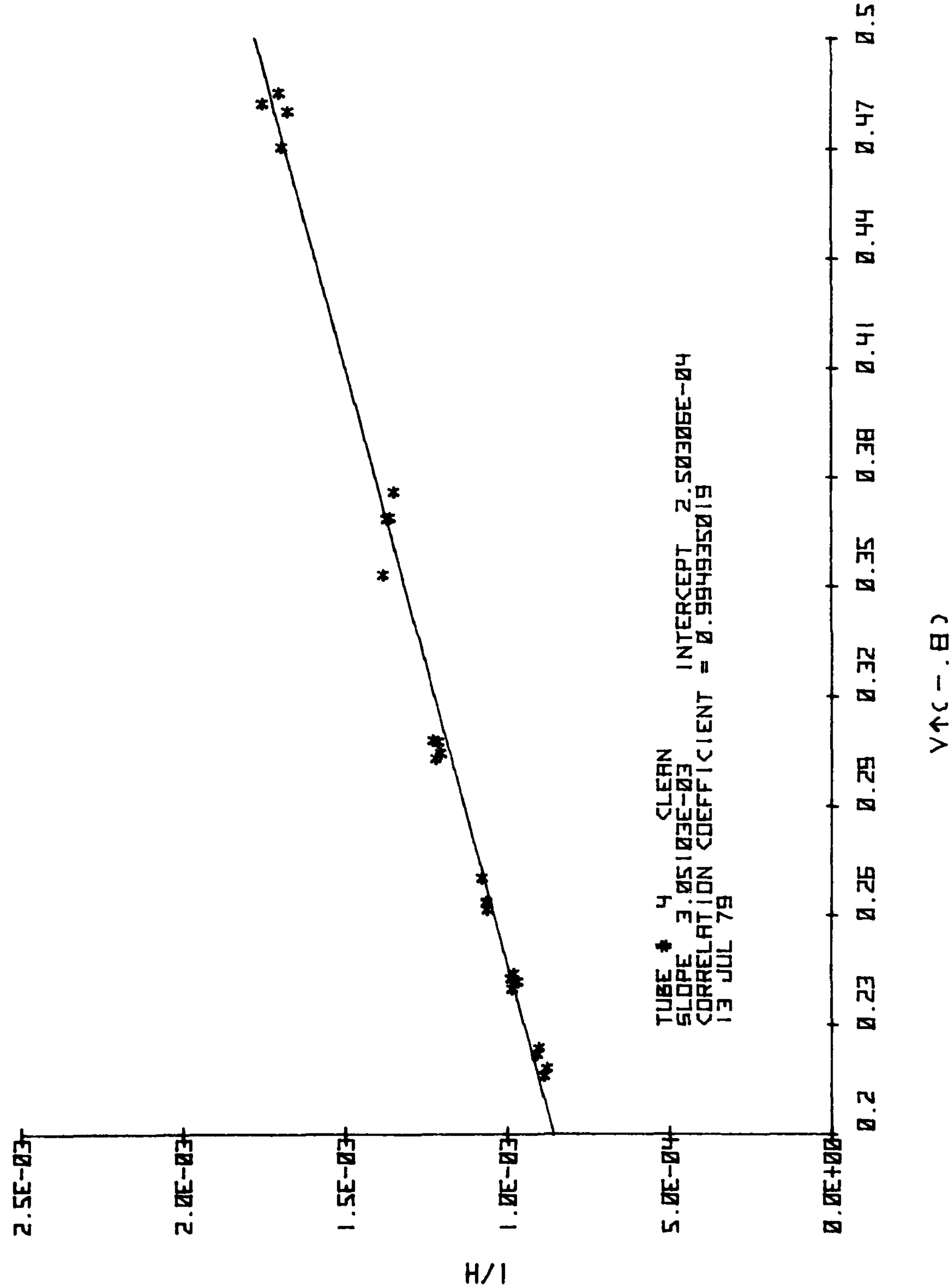

TUBE # 4 CLEAN
SLOPE 3.05103E-03 INTERCEPT 2.50306E-04
CORRELATION COEFFICIENT = 0.994935019
13 JUL 79
H/I
V↑(-.8)
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
2.5E-03
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-38

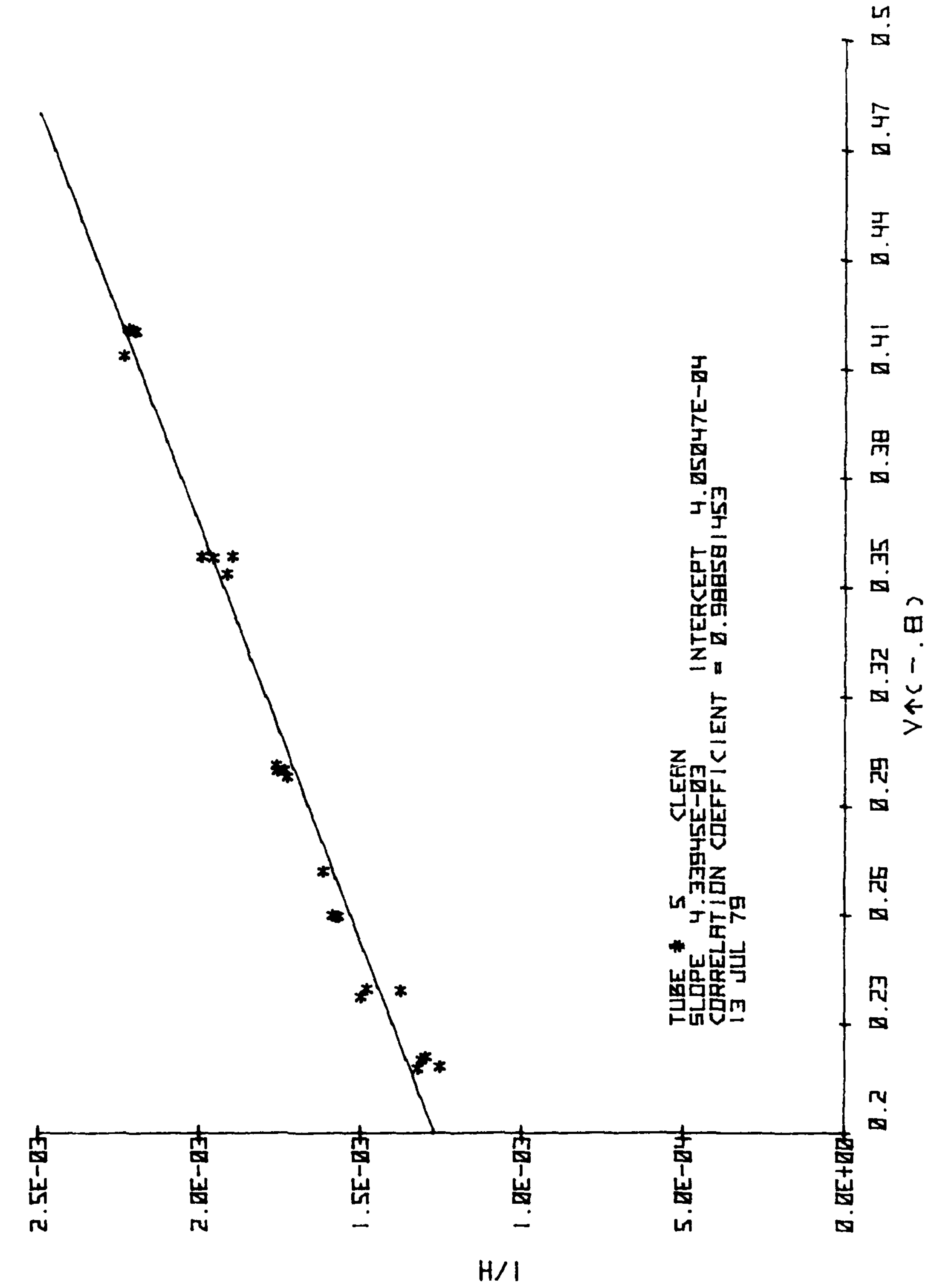

TUBE # 5 CLEAN
SLOPE 4.33945E-03 INTERCEPT 4.05047E-04
CORRELATION COEFFICIENT = 0.988581453
13 JUL 79
H/I
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
2.5E-03
V↑(-.8)
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-39

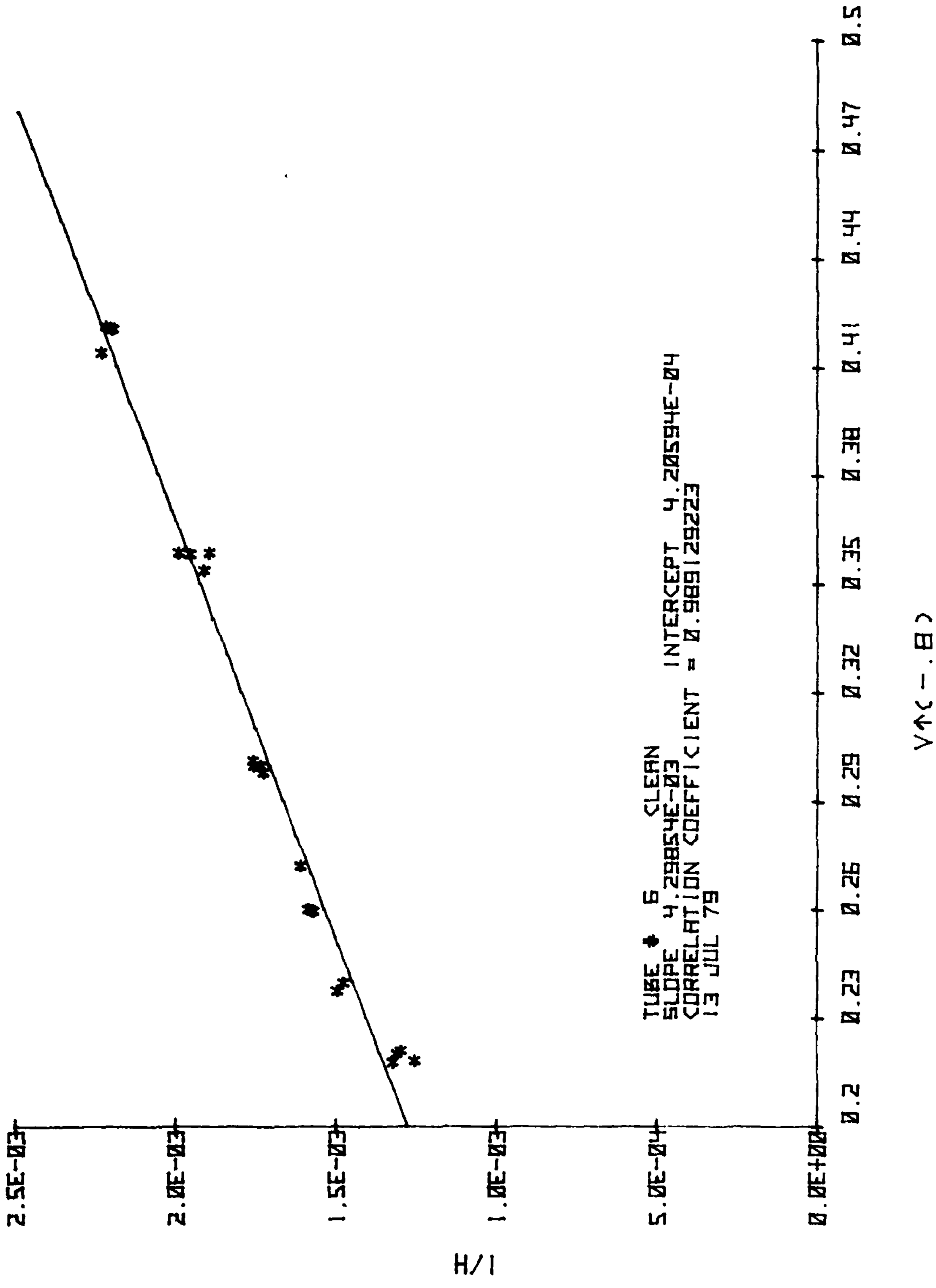

TUBE # 6 CLEAN
SLOPE 4.29854E-03 INTERCEPT 4.20594E-04
CORRELATION COEFFICIENT = 0.989129223
13 JUL 79
H/I
V↑(-.8)
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
2.5E-03

FIGURE B-40

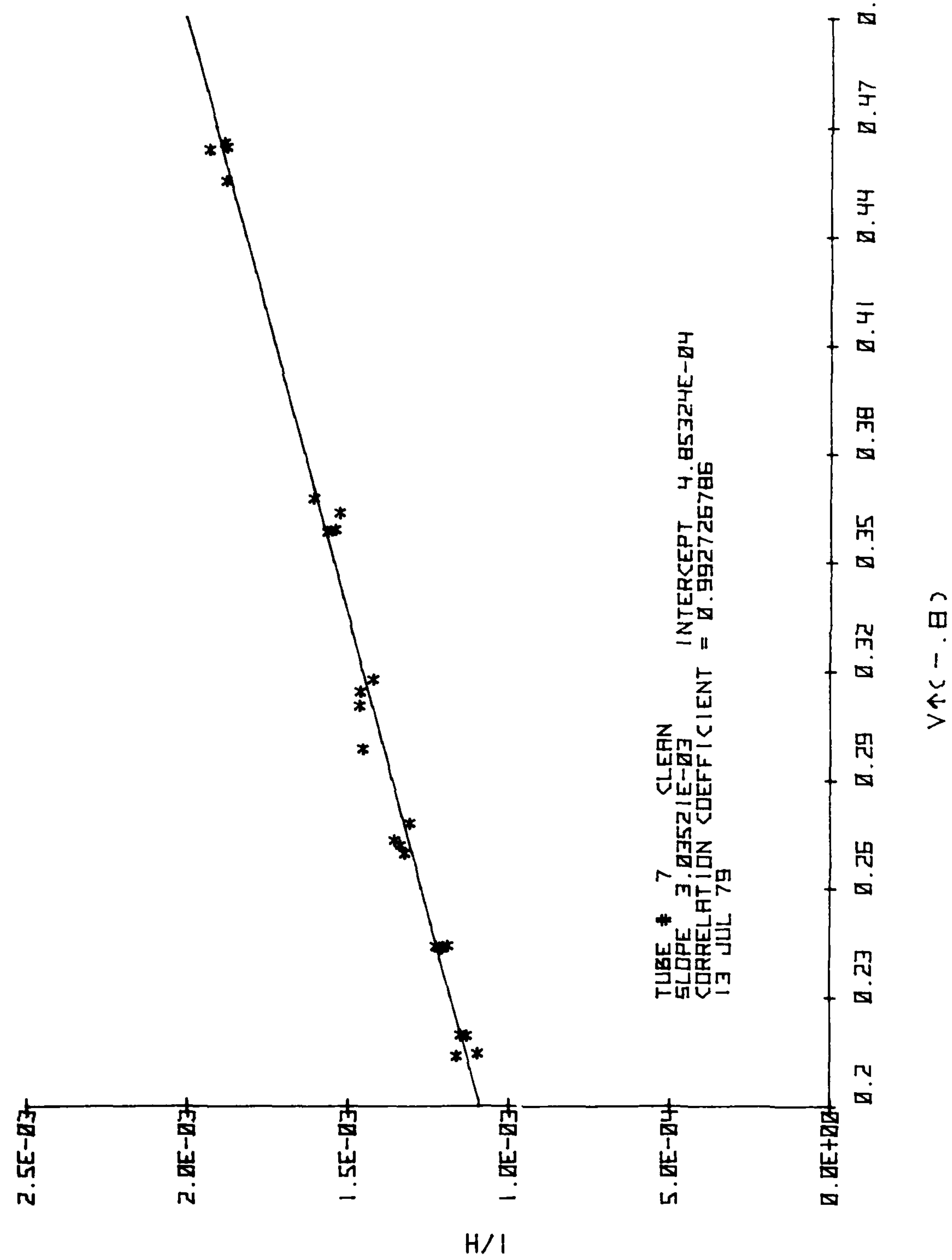

TUBE # 7 CLEAN
SLOPE 3.03521E-03 INTERCEPT 4.85324E-04
CORRELATION COEFFICIENT = 0.99272678G
13 JUL 79
H/I
V↑(-.8)
2.5E-03
2.0E-03
1.5E-03
1.0E-03
5.0E-04
0.0E+00
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-41

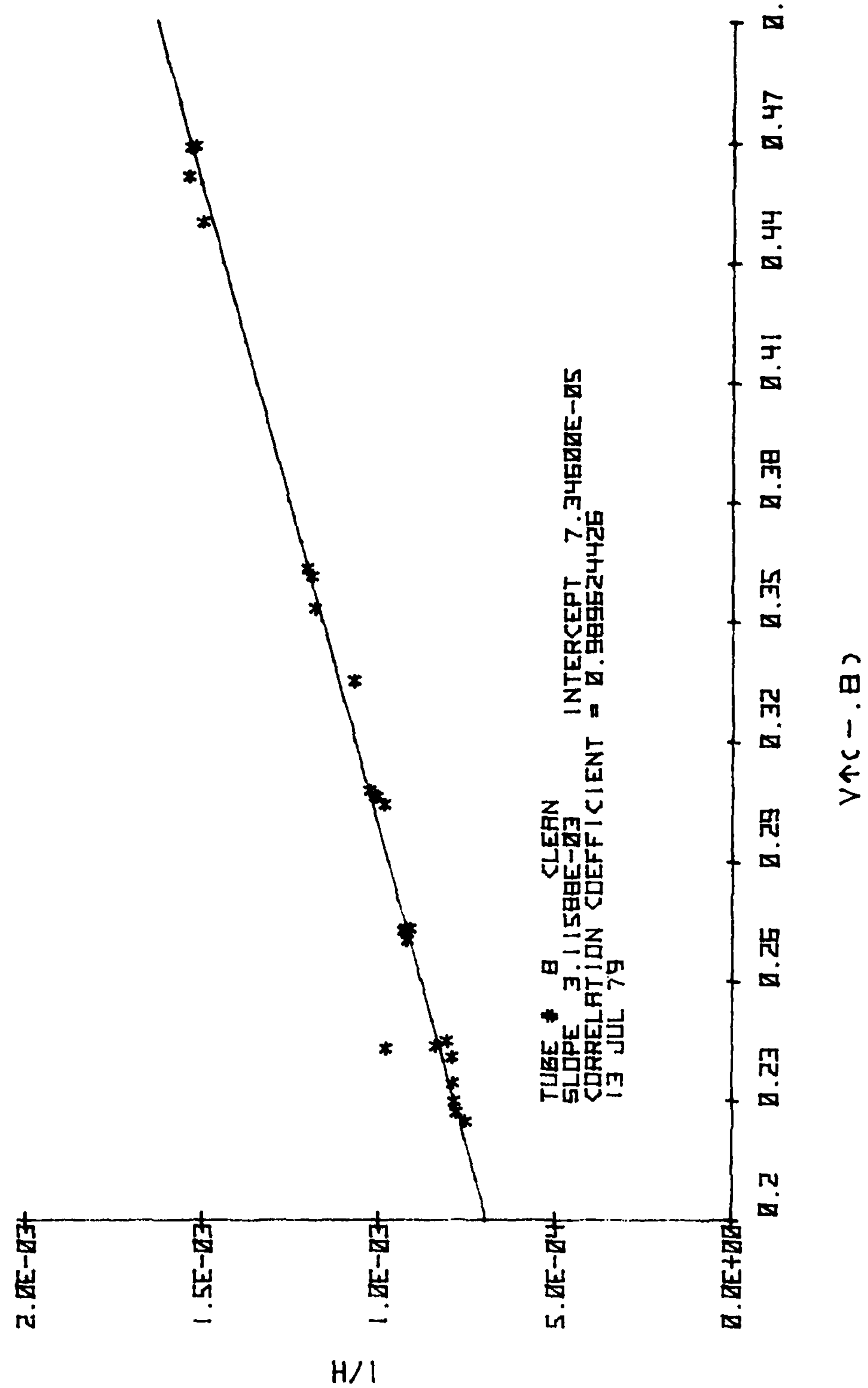

TUBE # 8 CLEAN
SLOPE 3.115880E-03 INTERCEPT 7.346000E-05
CORRELATION COEFFICIENT = 0.989524426
13 JUL 79
H/I
V↑(-.8)
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-42

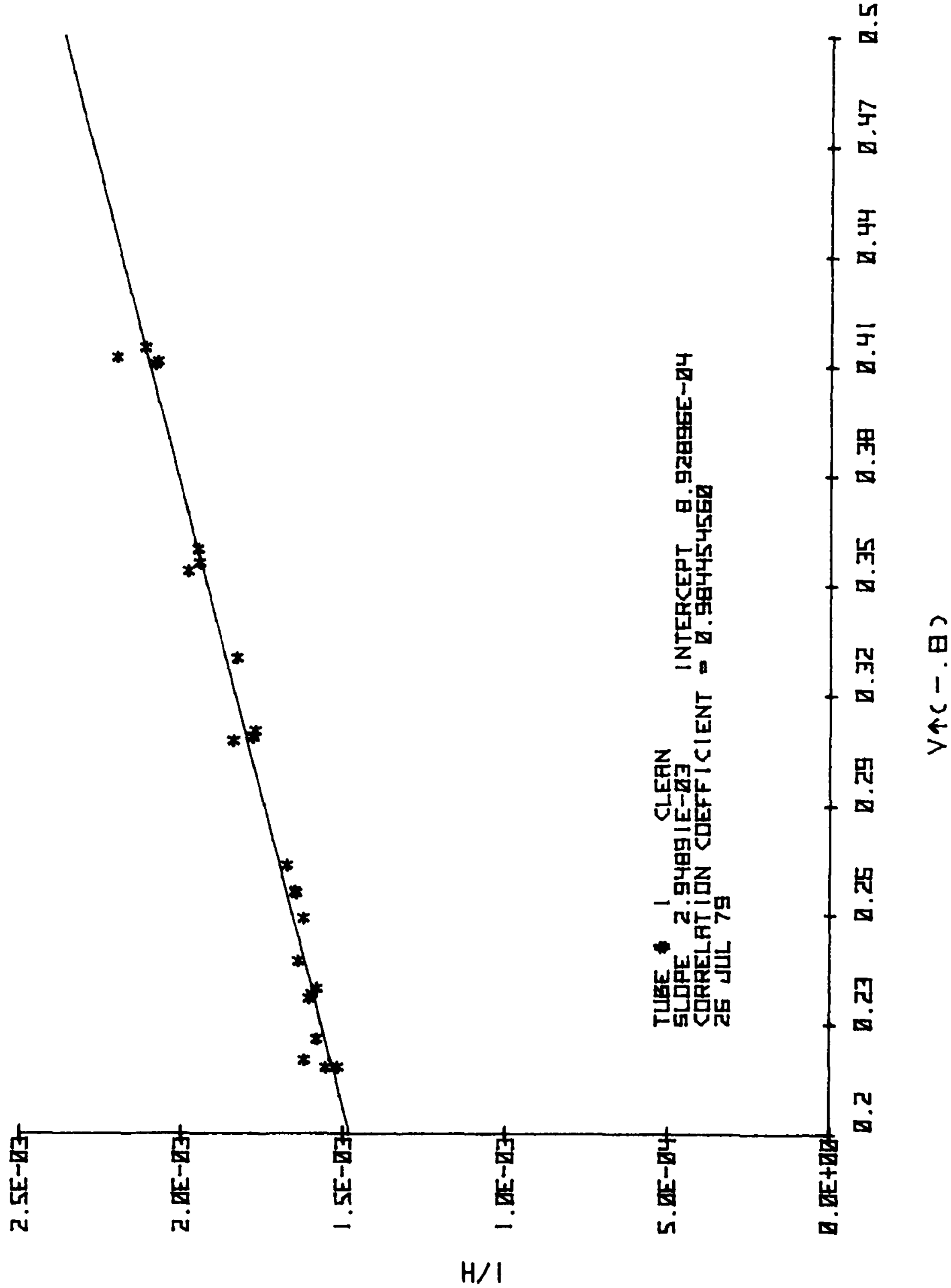

TUBE # 1 CLEAN
SLOPE 2.94891E-03 INTERCEPT 8.92896E-04
CORRELATION COEFFICIENT = 0.984454560
25 JUL 79
H/I
V↑(-.8)
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
2.5E-03
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-43

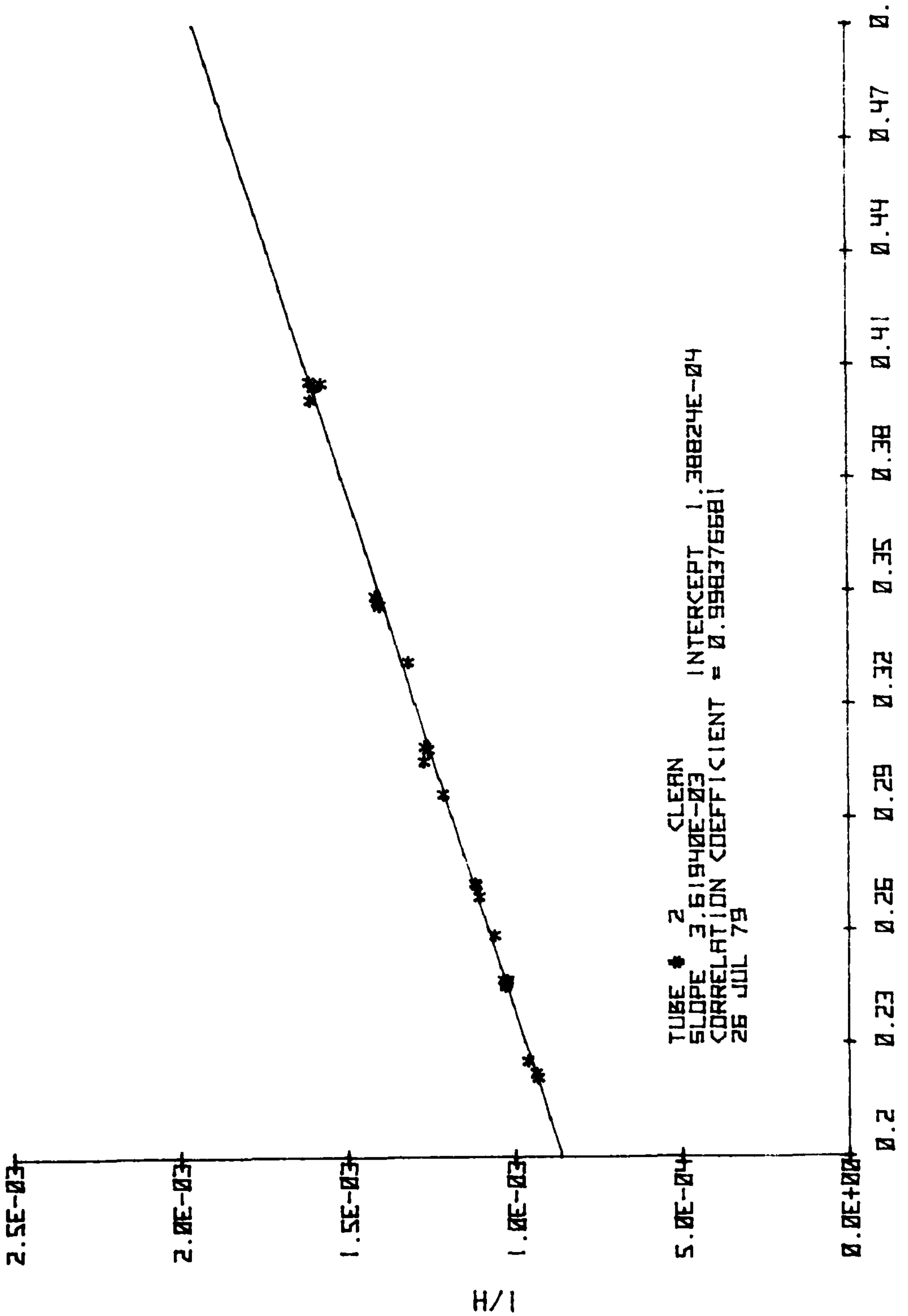

TUBE # 2 CLEAN
SLOPE 3.61940E-03 INTERCEPT 1.38824E-04
CORRELATION COEFFICIENT = 0.998376681
26 JUL 79
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V^(-.8)
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
2.5E-03
H/I

FIGURE B-44

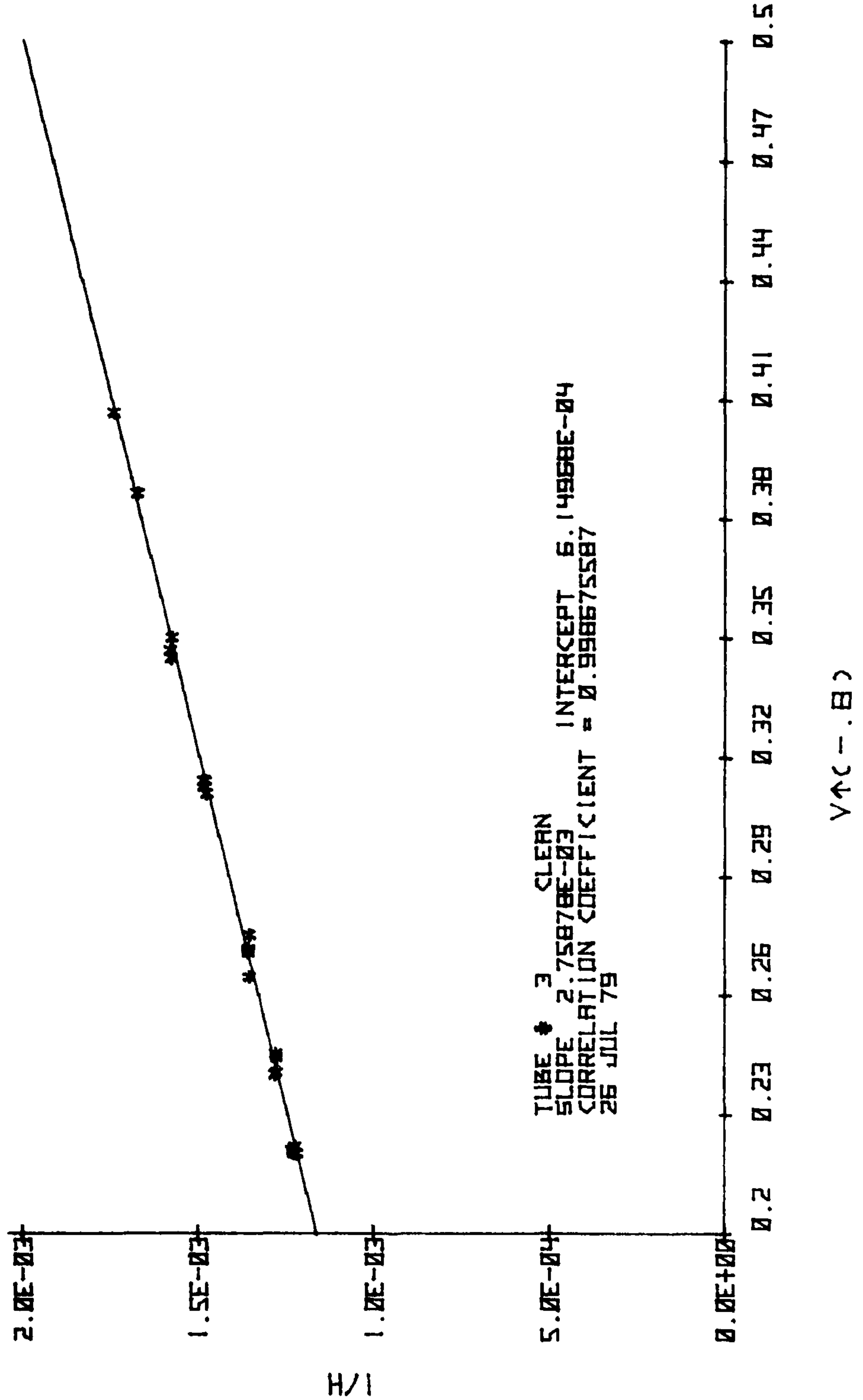

TUBE # 3 CLEAN
SLOPE 2.75878E-03 INTERCEPT 6.14968E-04
CORRELATION COEFFICIENT = 0.998675587
26 JUL 79
2.0E-03
1.5E-03
1.0E-03
5.0E-04
0.0E+00
H/I
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-45

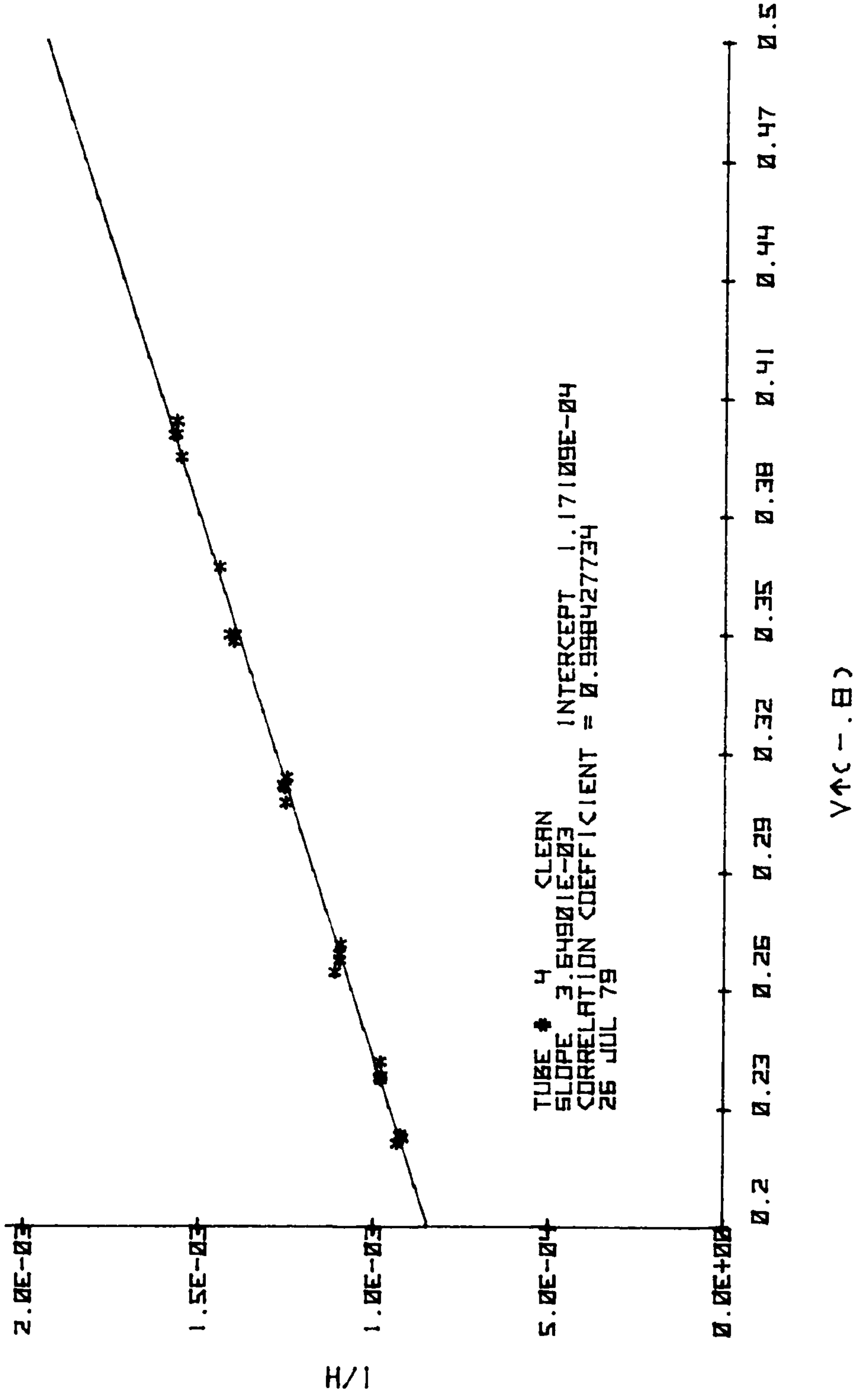

TUBE # 4 CLEAN
SLOPE 3.64901E-03 INTERCEPT 1.17109E-04
CORRELATION COEFFICIENT = 0.998427734
26 JUL 79
2.0E-03
1.5E-03
1.0E-03
5.0E-04
0.0E+00
1/H
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-46

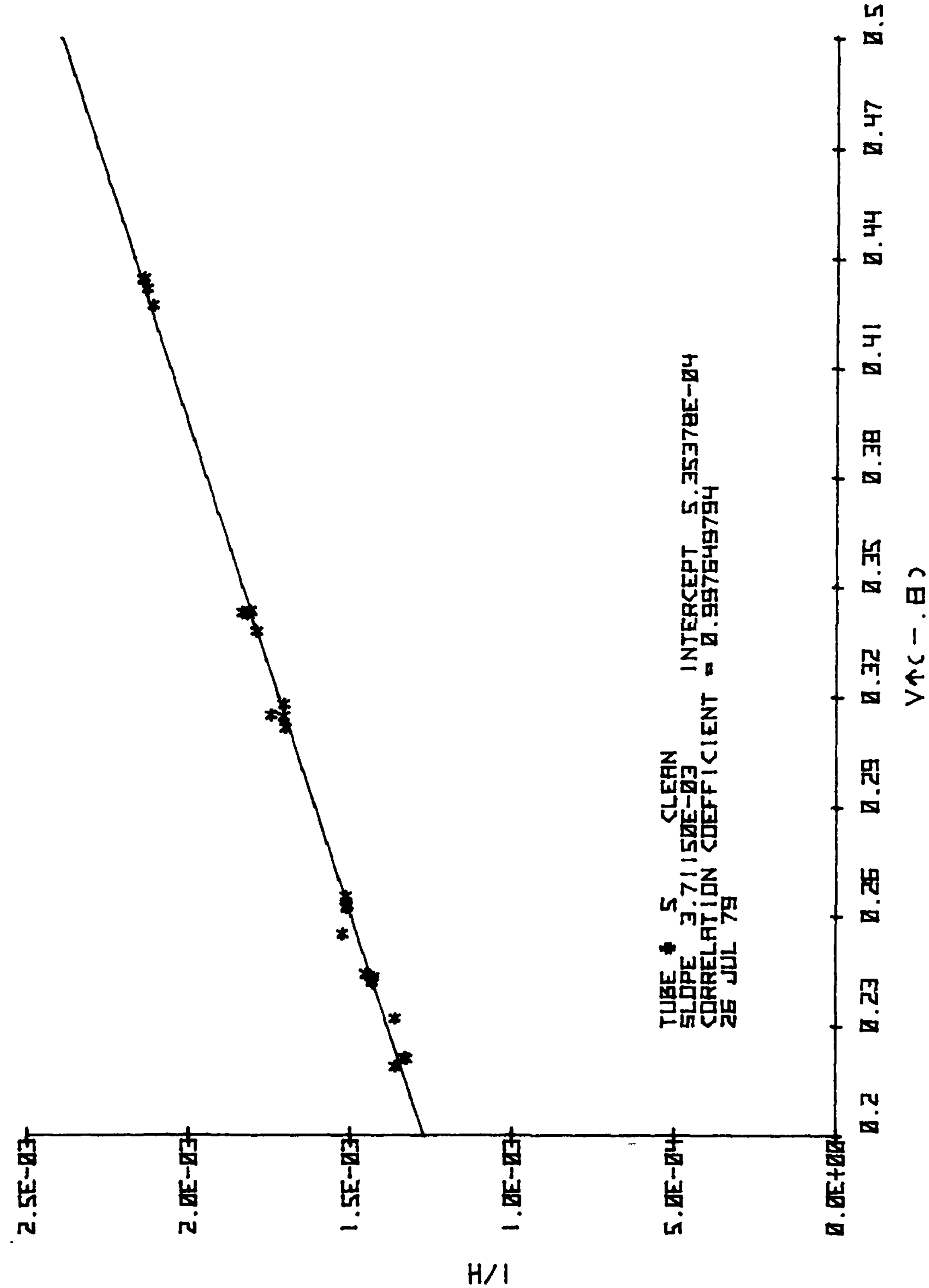

TUBE # 5 CLEAN
SLOPE 3.71150E-03 INTERCEPT 5.35378E-04
CORRELATION COEFFICIENT = 0.997649794
26 JUL 79
2.5E-03
2.0E-03
1.5E-03
1.0E-03
5.0E-04
0.0E+00
H/I
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-47

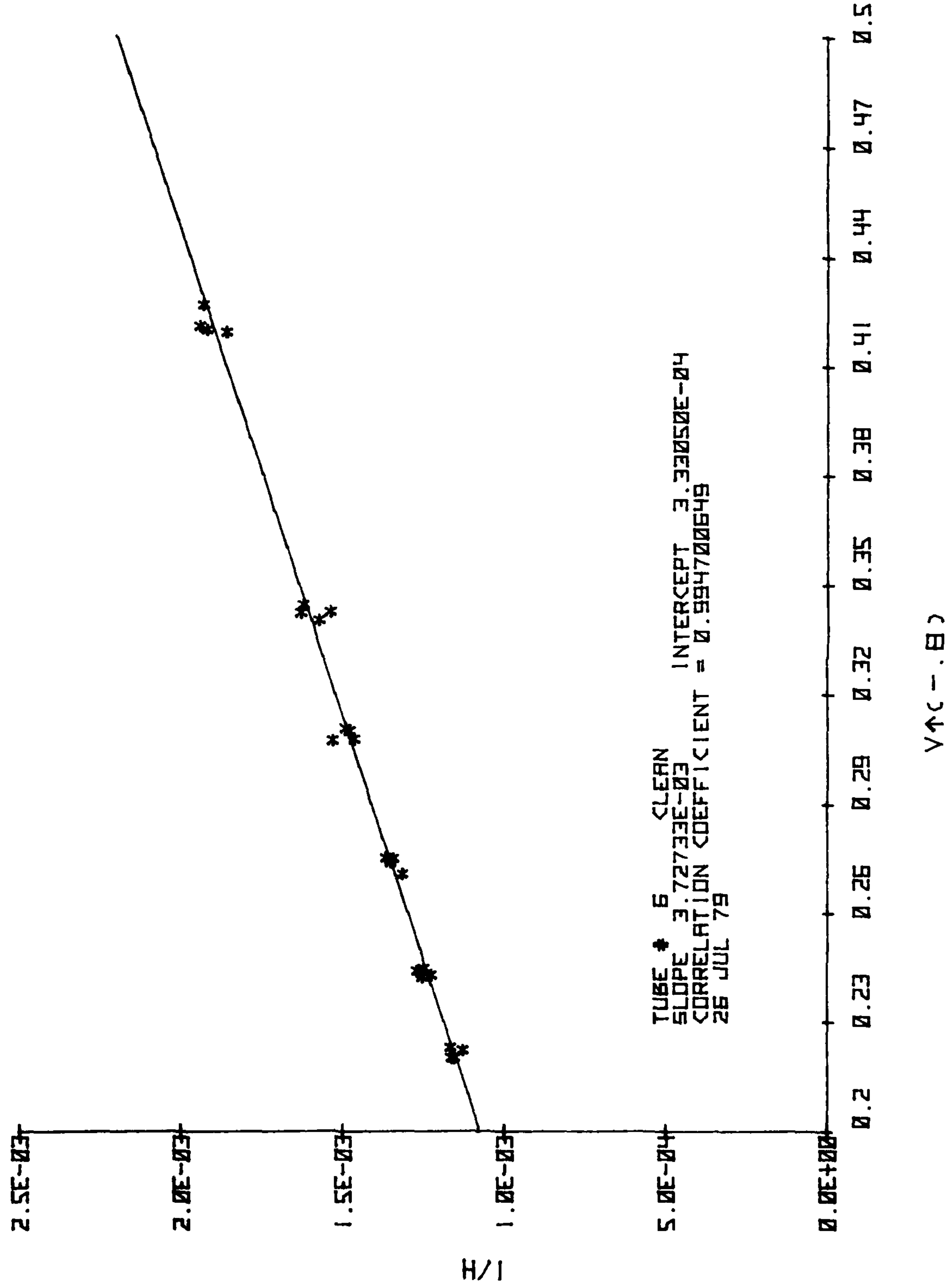

TUBE # 6 CLEAN
SLOPE 3.72733E-03 INTERCEPT 3.33050E-04
CORRELATION COEFFICIENT = 0.994700649
26 JUL 79
2.5E-03
2.0E-03
1.5E-03
1.0E-03
5.0E-04
0.0E+00
I/H
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-48

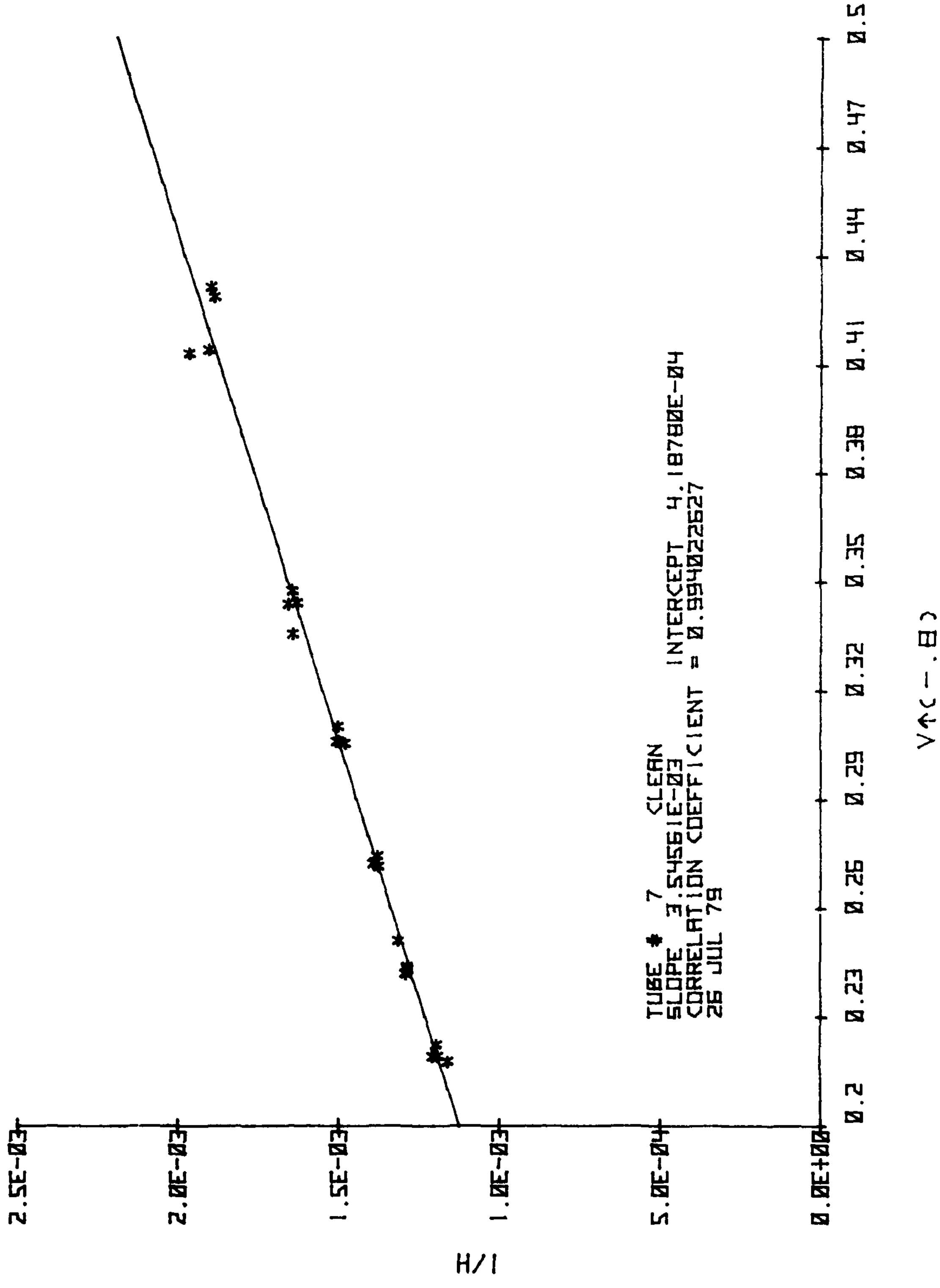

TUBE # 7 CLEAN
SLOPE 3.54561E-03 INTERCEPT 4.18780E-04
CORRELATION COEFFICIENT = 0.994022627
26 JUL 79
H/I
V↑(-.8)
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
2.5E-03
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-49

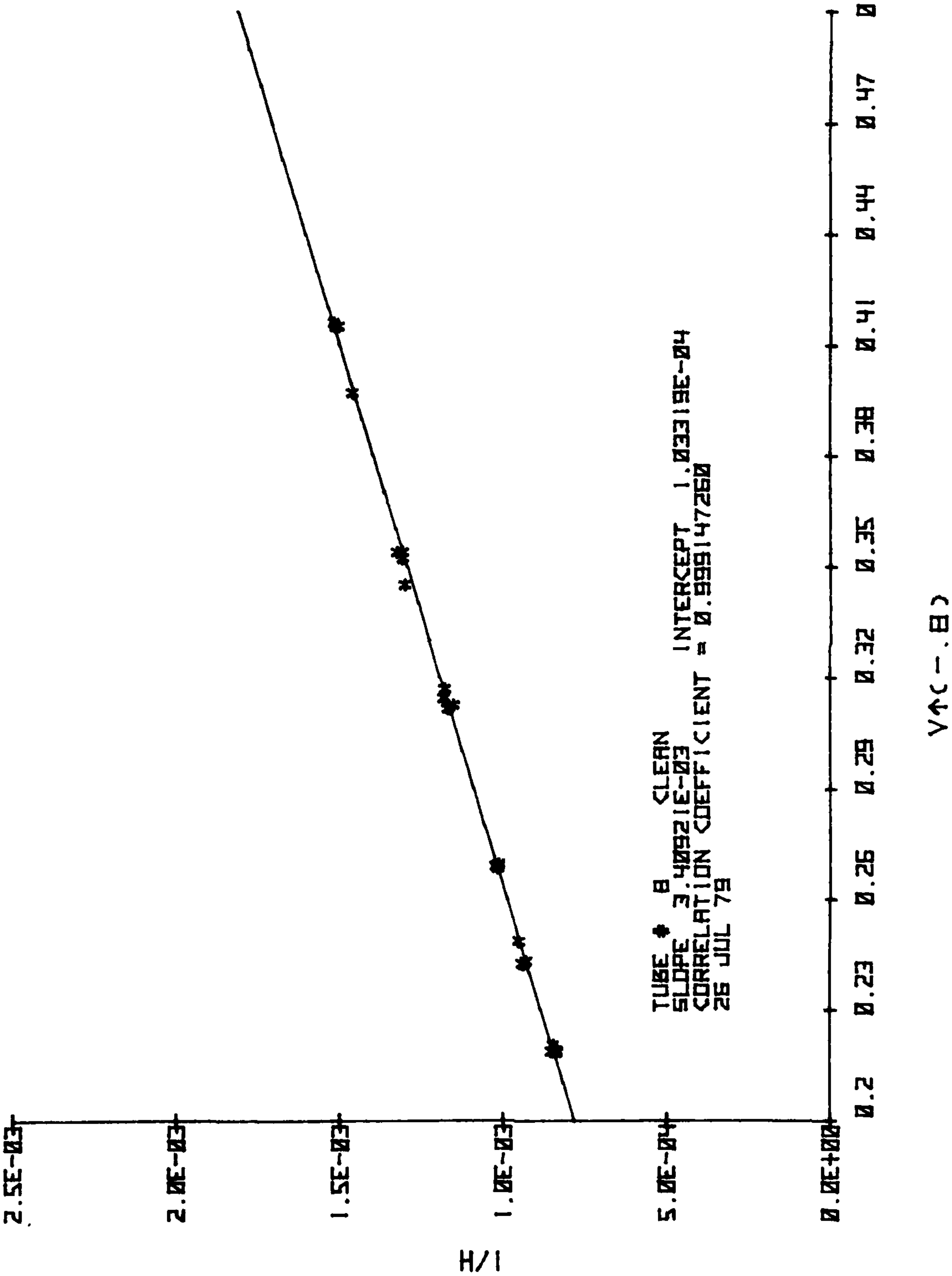

TUBE # 8 CLEAN
SLOPE 3.40921E-03 INTERCEPT 1.03319E-04
CORRELATION COEFFICIENT = 0.999147260
26 JUL 79
H/I
V↑(-.8)
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
2.5E-03
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-50

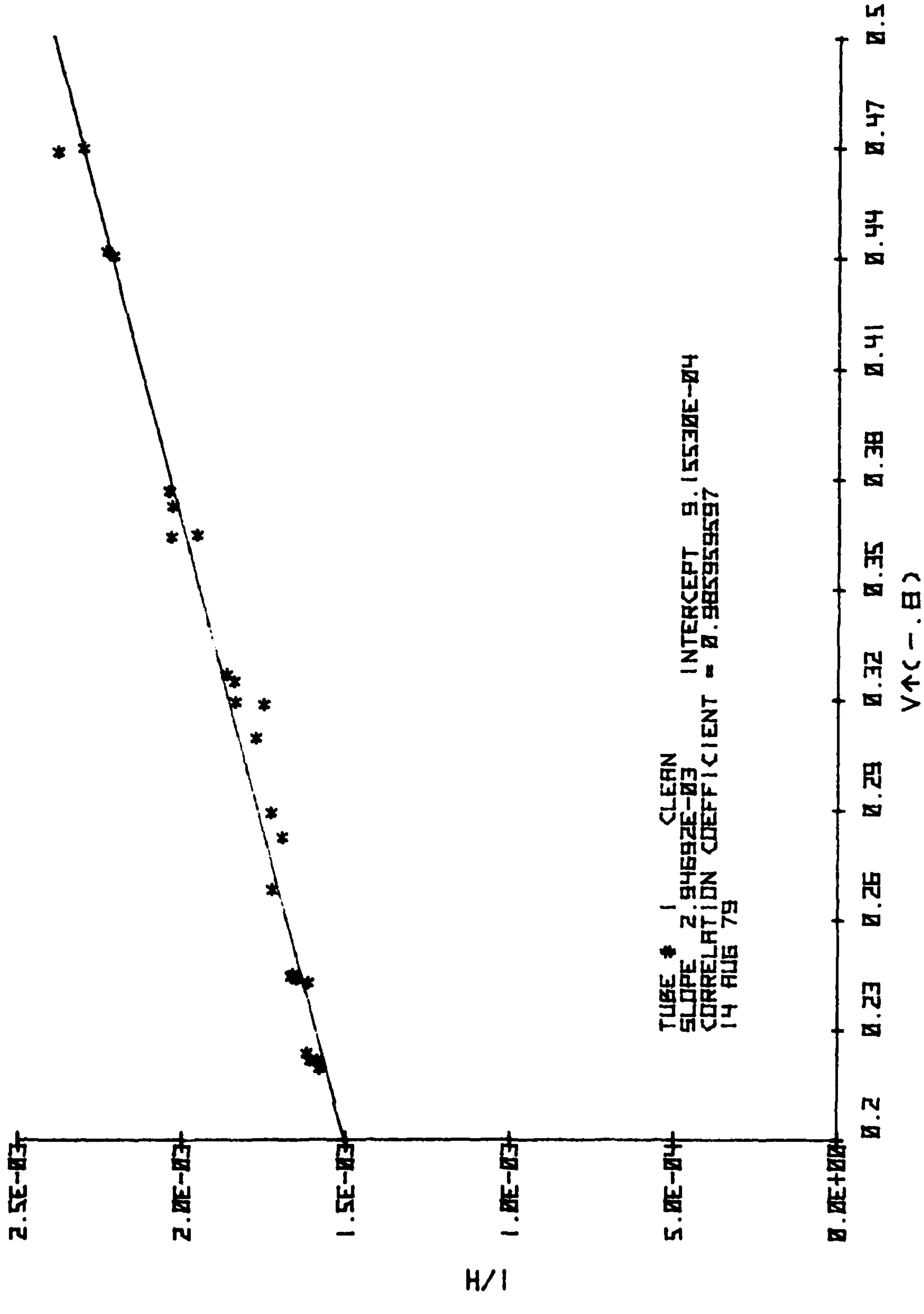

TUBE # 1 CLEAN
SLOPE 2.94692E-03 INTERCEPT 9.15530E-04
CORRELATION COEFFICIENT = 0.985959597
14 AUG 79
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
2.5E-03
H/I

FIGURE B-51

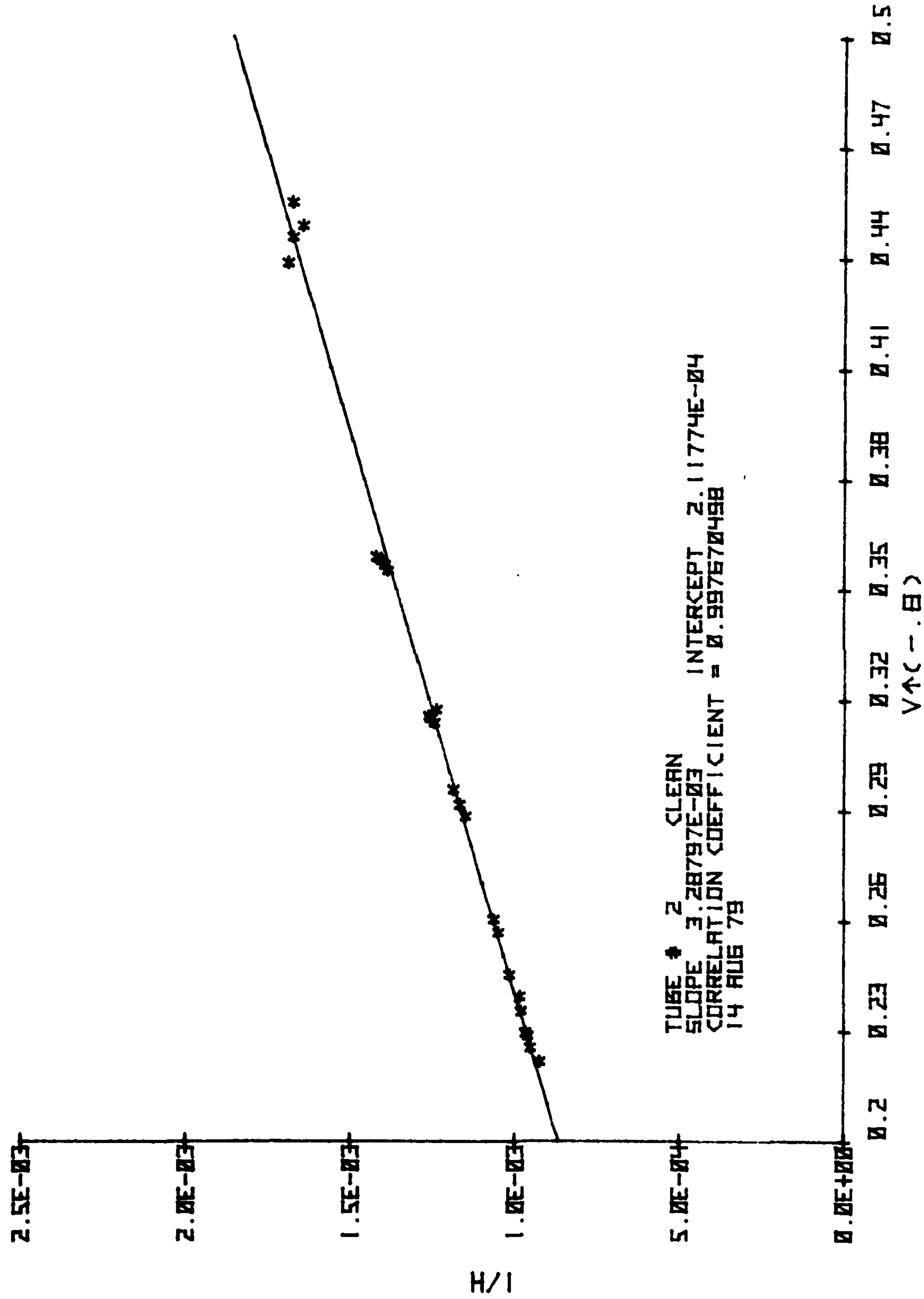

TUBE # 2 CLEAN
SLOPE 3.28797E-03 INTERCEPT 2.11774E-04
CORRELATION COEFFICIENT = 0.997670498
14 AUG 79
V↑(-.8)
H/I
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
2.5E-03

FIGURE B-52

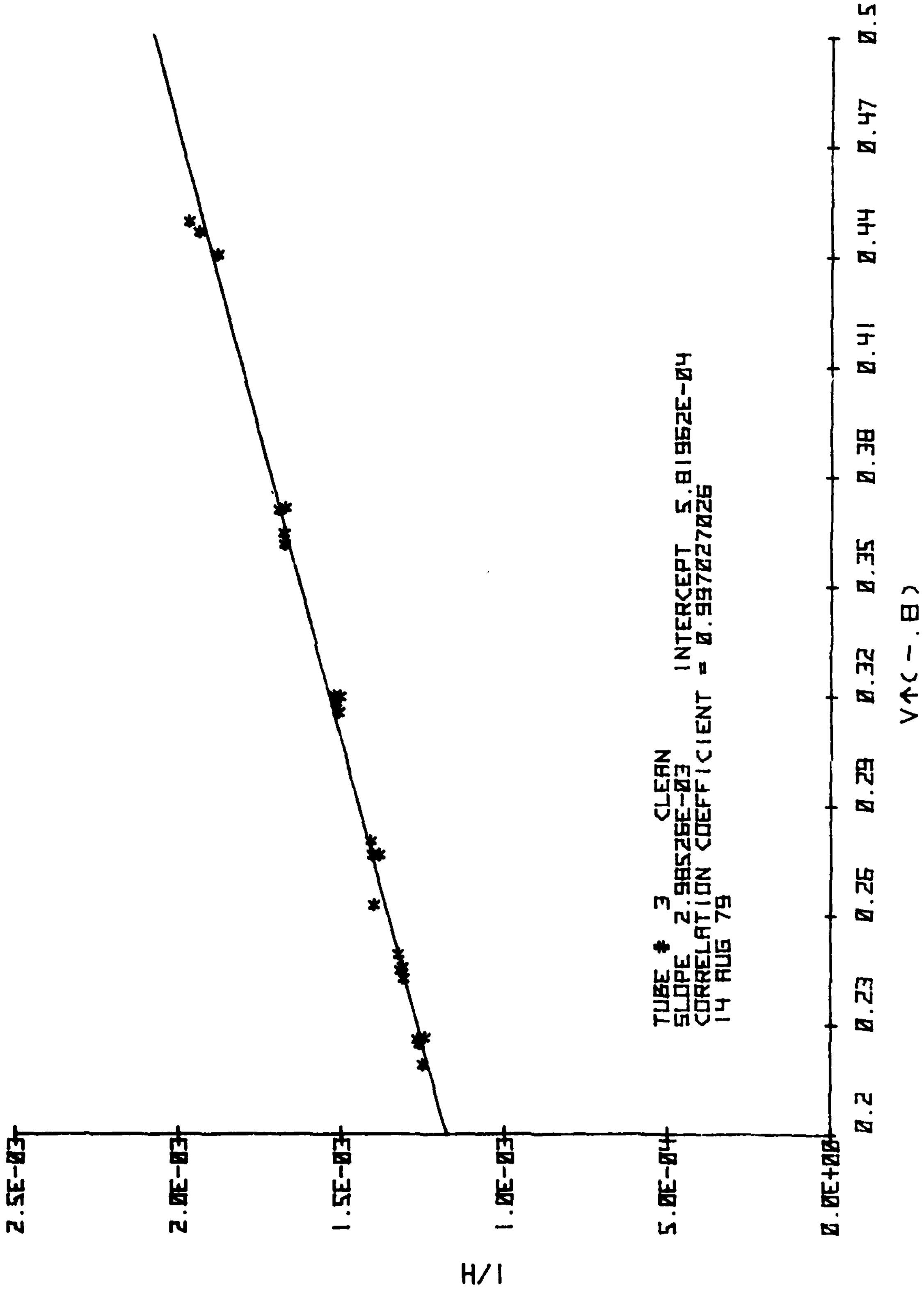

TUBE # 3 CLEAN
SLOPE 2.98526E-03 INTERCEPT 5.81962E-04
CORRELATION COEFFICIENT = 0.997027026
14 AUG 79
H/I
V↑(-.8)
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
2.5E-03
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-53

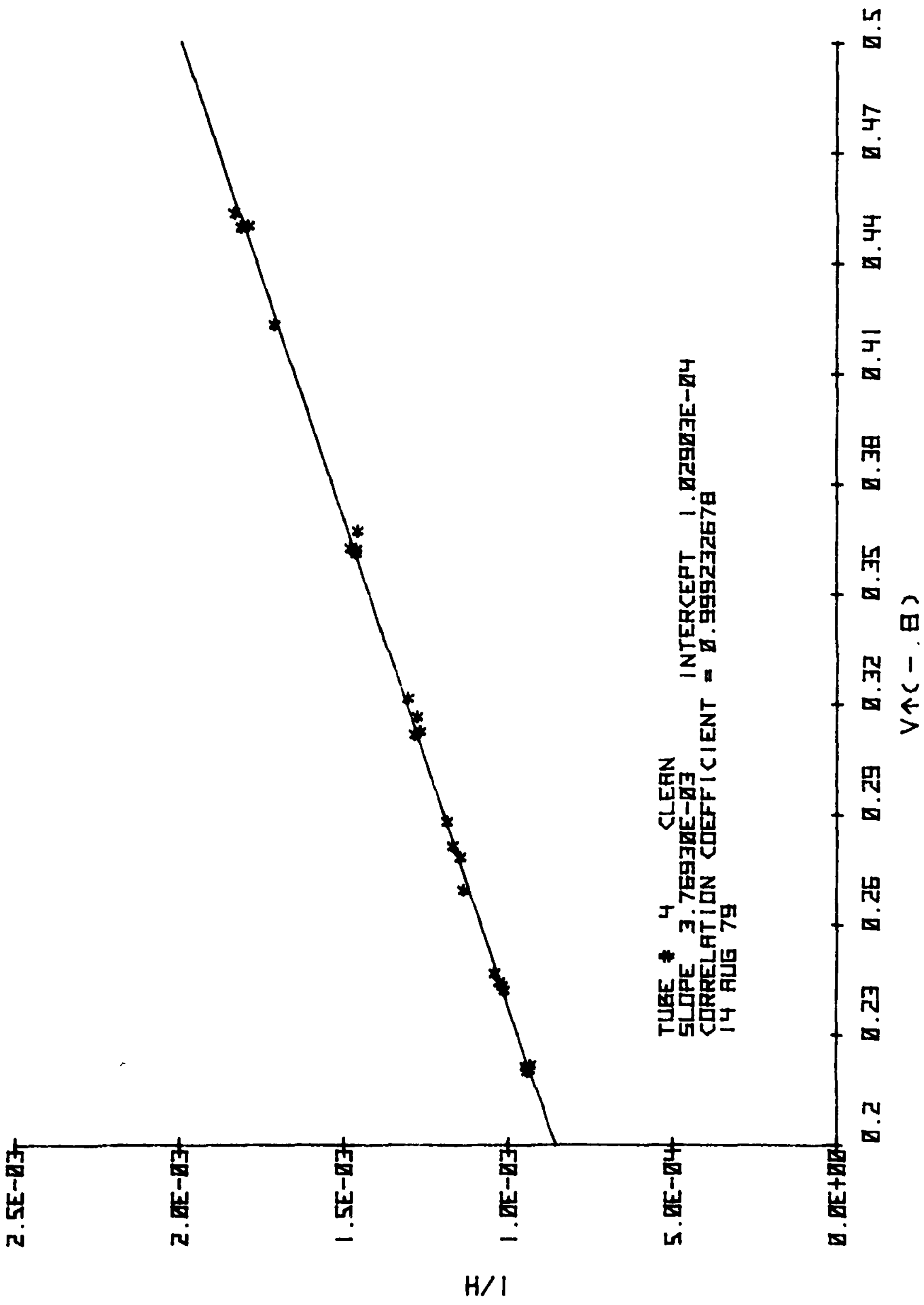

TUBE # 4 CLEAN
SLOPE 3.76930E-03 INTERCEPT 1.02903E-04
CORRELATION COEFFICIENT = 0.999232678
14 AUG 79
V↑(- .8)
H/I
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
2.5E-03

FIGURE B-54

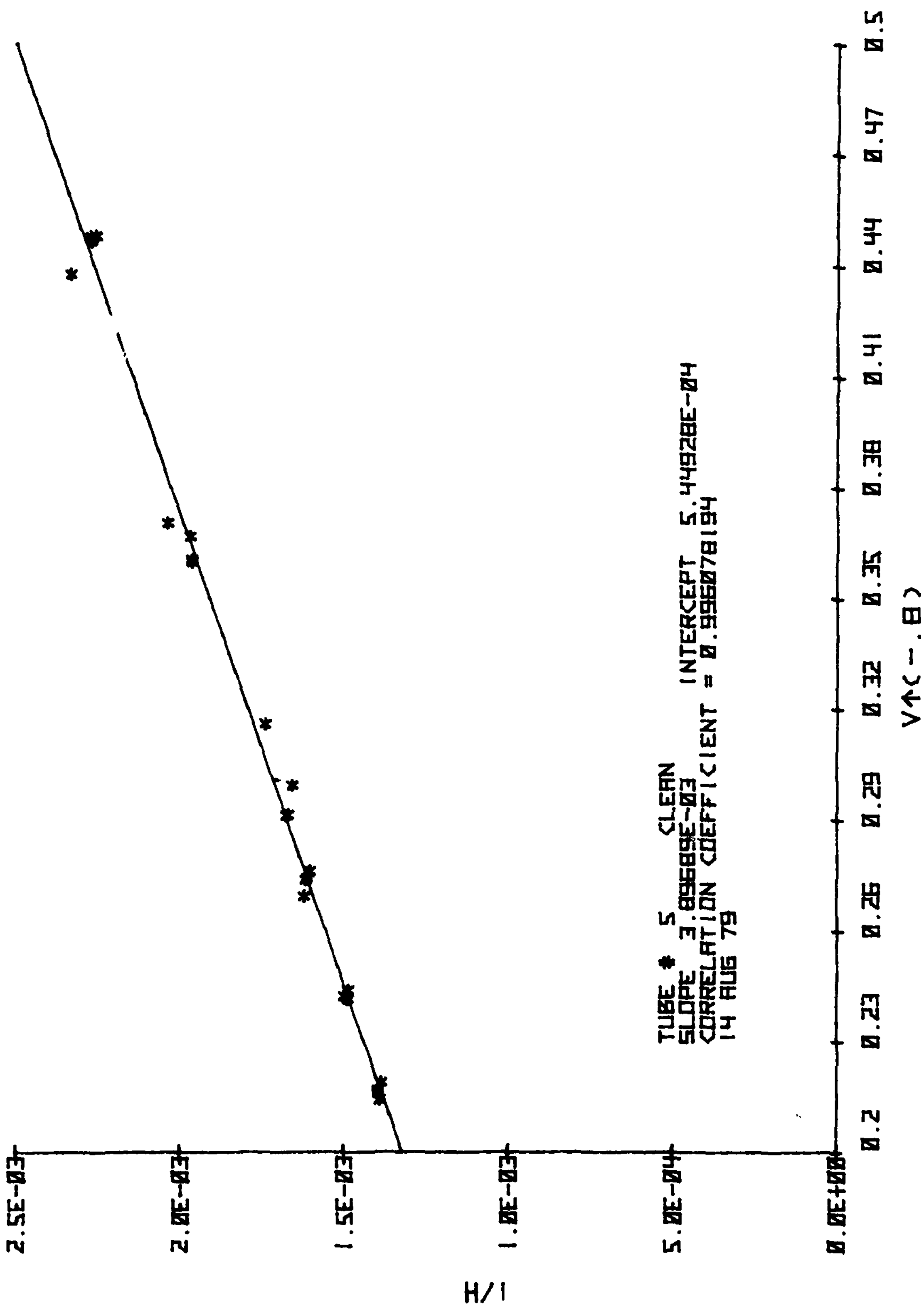

TUBE # 5 CLEAN
SLOPE 3.89689E-03 INTERCEPT 5.44928E-04
CORRELATION COEFFICIENT = 0.996078194
14 AUG 79
V^(-.8)
H/I
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
2.5E-03

FIGURE B-55

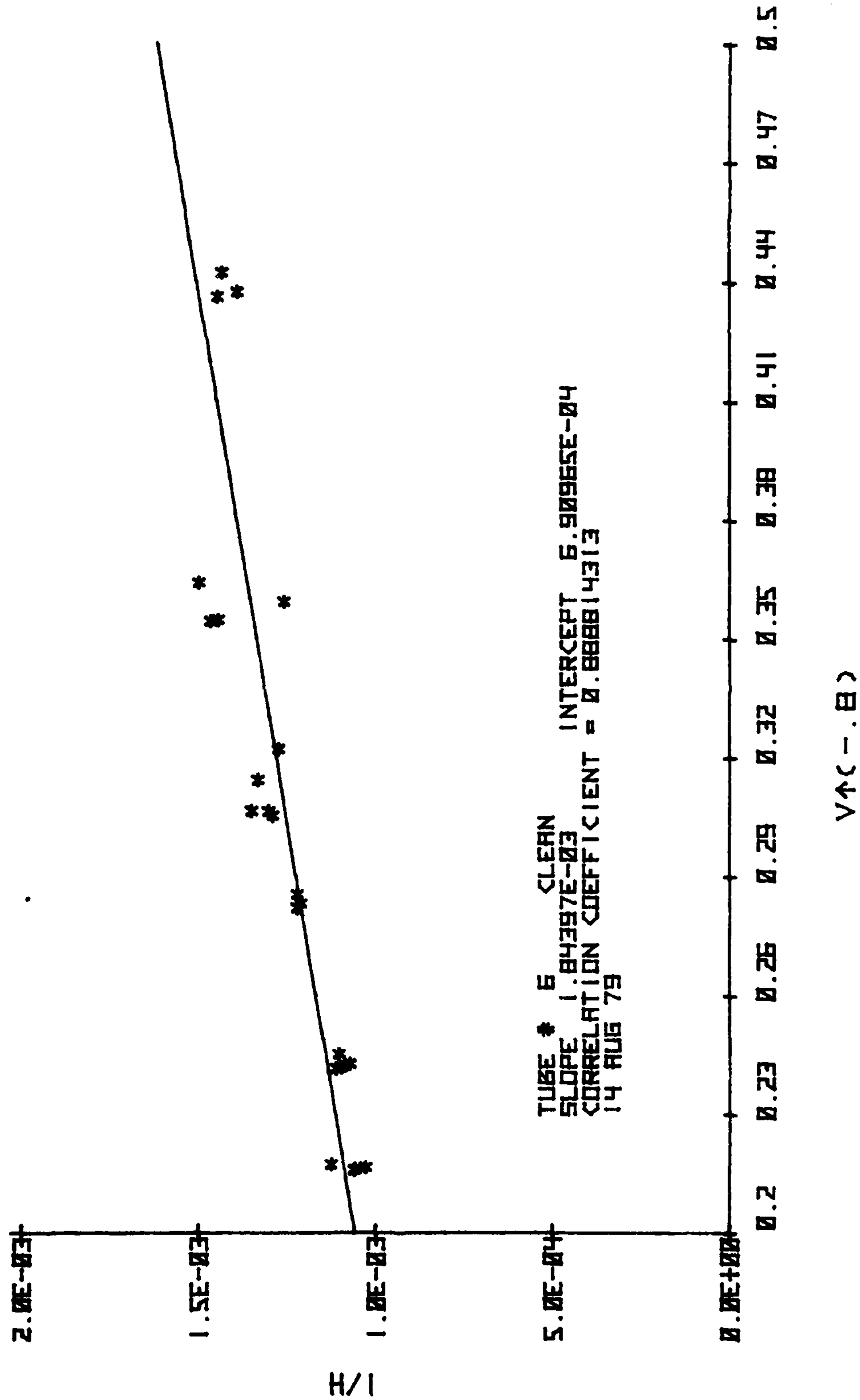

TUBE # 6 CLEAN
SLOPE 1.84397E-03 INTERCEPT 6.90965E-04
CORRELATION COEFFICIENT = 0.888814313
14 AUG 79
H/I
V↑(-.8)
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-56

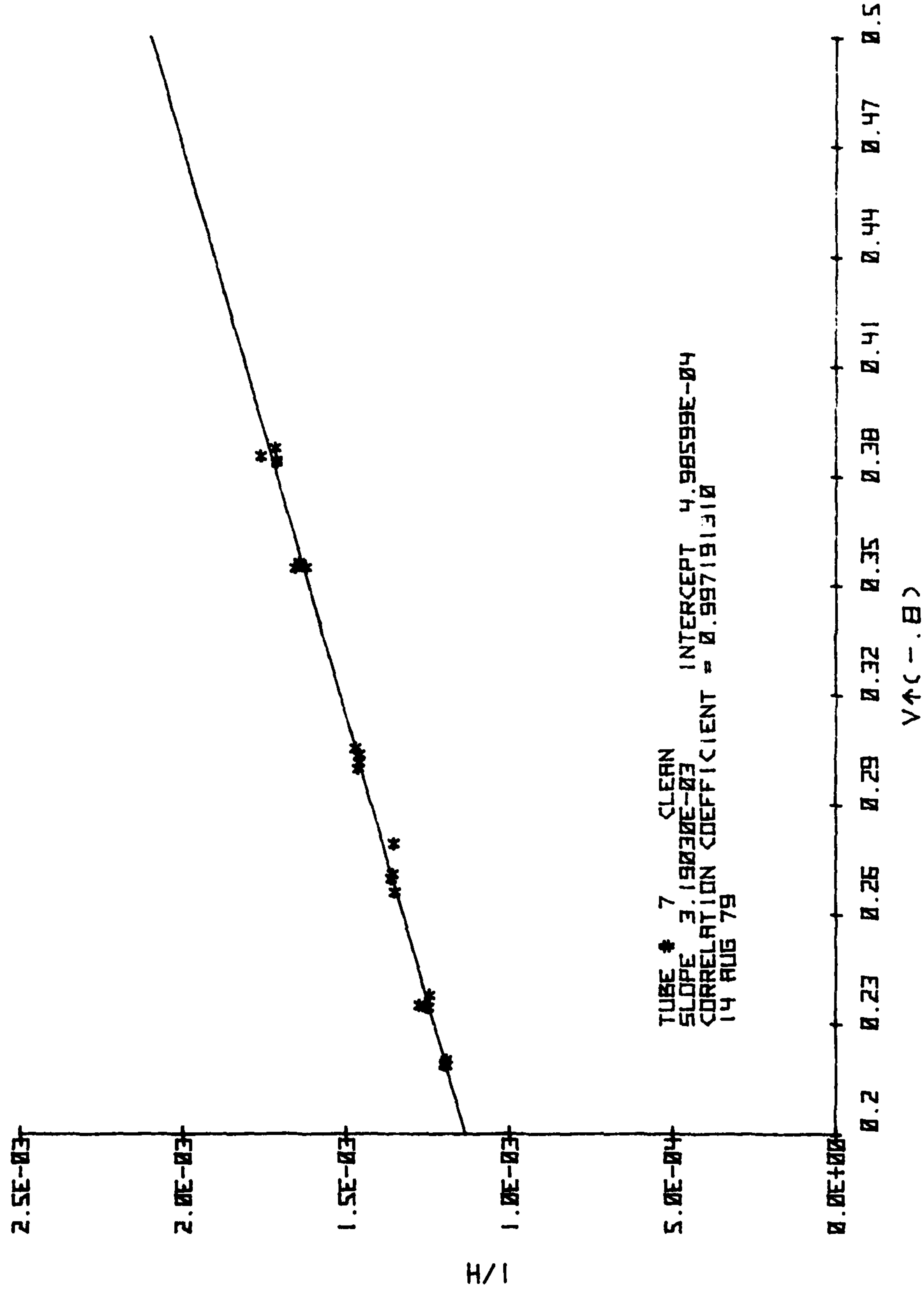

TUBE # 7 CLEAN
SLOPE 3.19030E-03 INTERCEPT 4.98599E-04
CORRELATION COEFFICIENT = 0.997191310
14 AUG 79
2.5E-03
2.0E-03
1.5E-03
1.0E-03
5.0E-04
0.0E+00
H/I
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-57

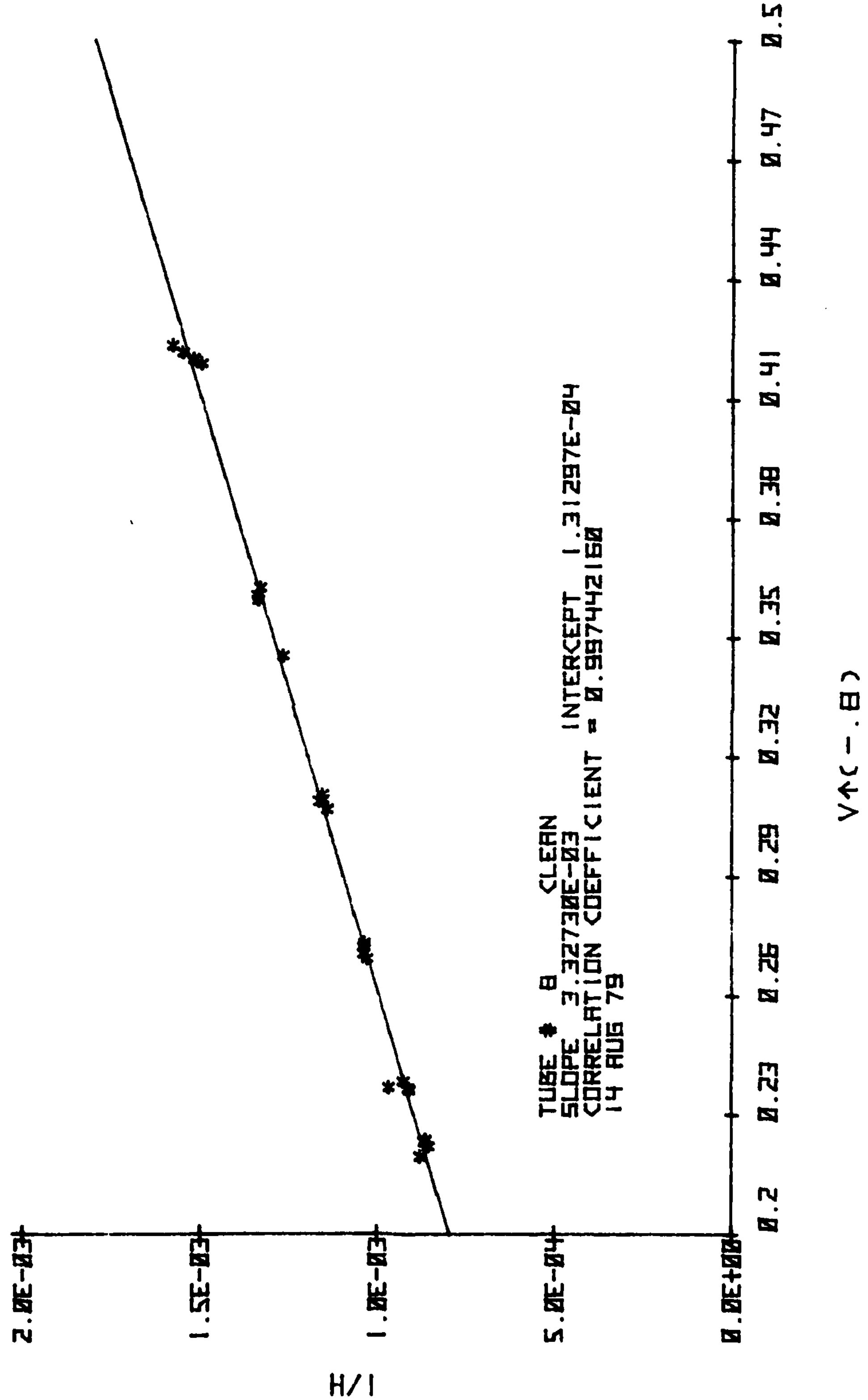

TUBE # 8 CLEAN
SLOPE 3.32730E-03 INTERCEPT 1.31297E-04
CORRELATION COEFFICIENT = 0.997442160
14 AUG 79
H/I
V↑(-.8)
0.0E+00
5.0E-04
1.0E-03
1.5E-03
2.0E-03
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-58

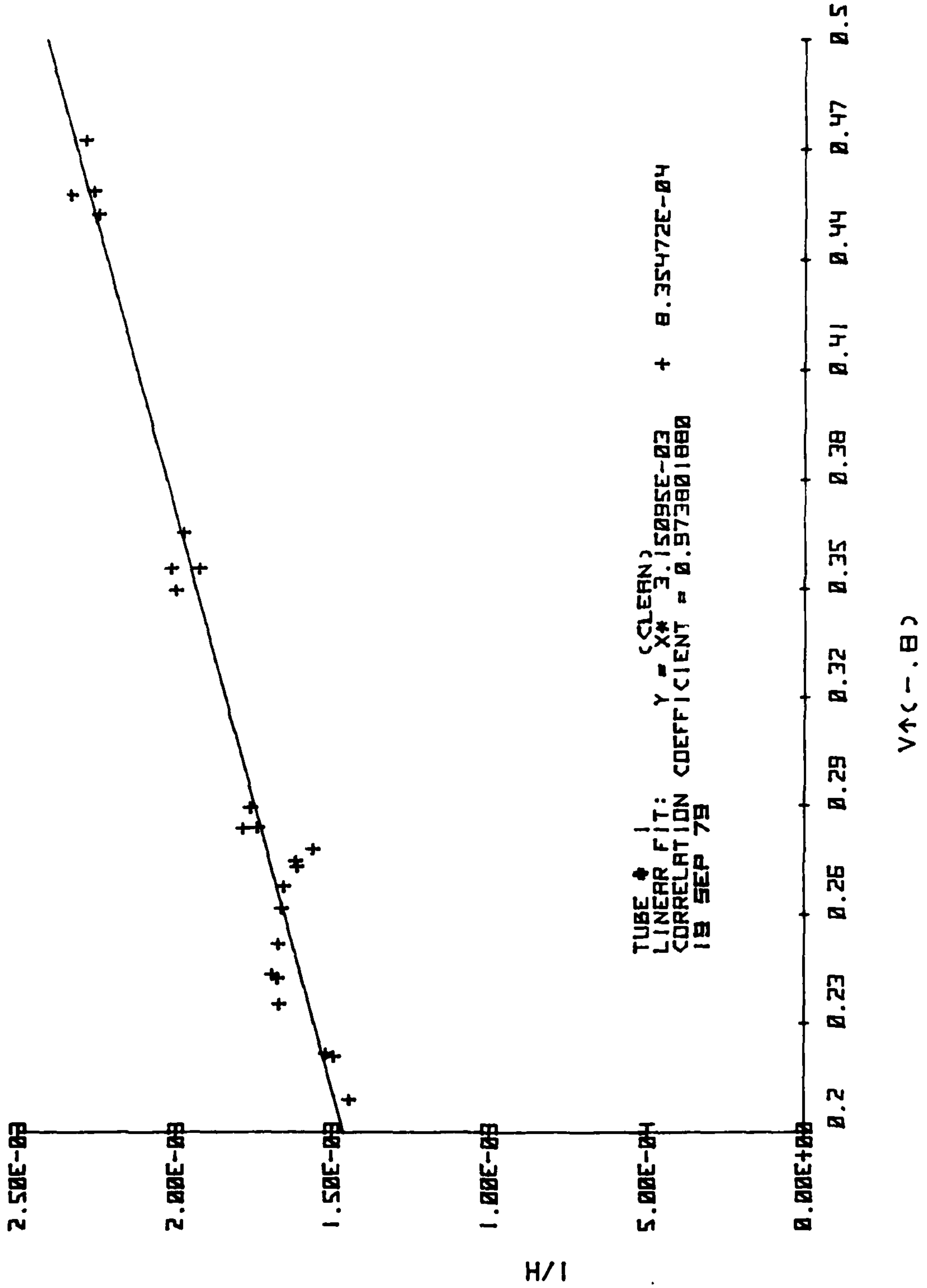

TUBE # 1 (CLEAN)
LINEAR FIT: Y = X* 3.15095E-03 + 8.35472E-04
CORRELATION COEFFICIENT = 0.973801880
19 SEP 79
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
0.00E+00
5.00E-04
1.00E-03
1.50E-03
2.00E-03
2.50E-03
V↑(-.8)
I/H

FIGURE B-59

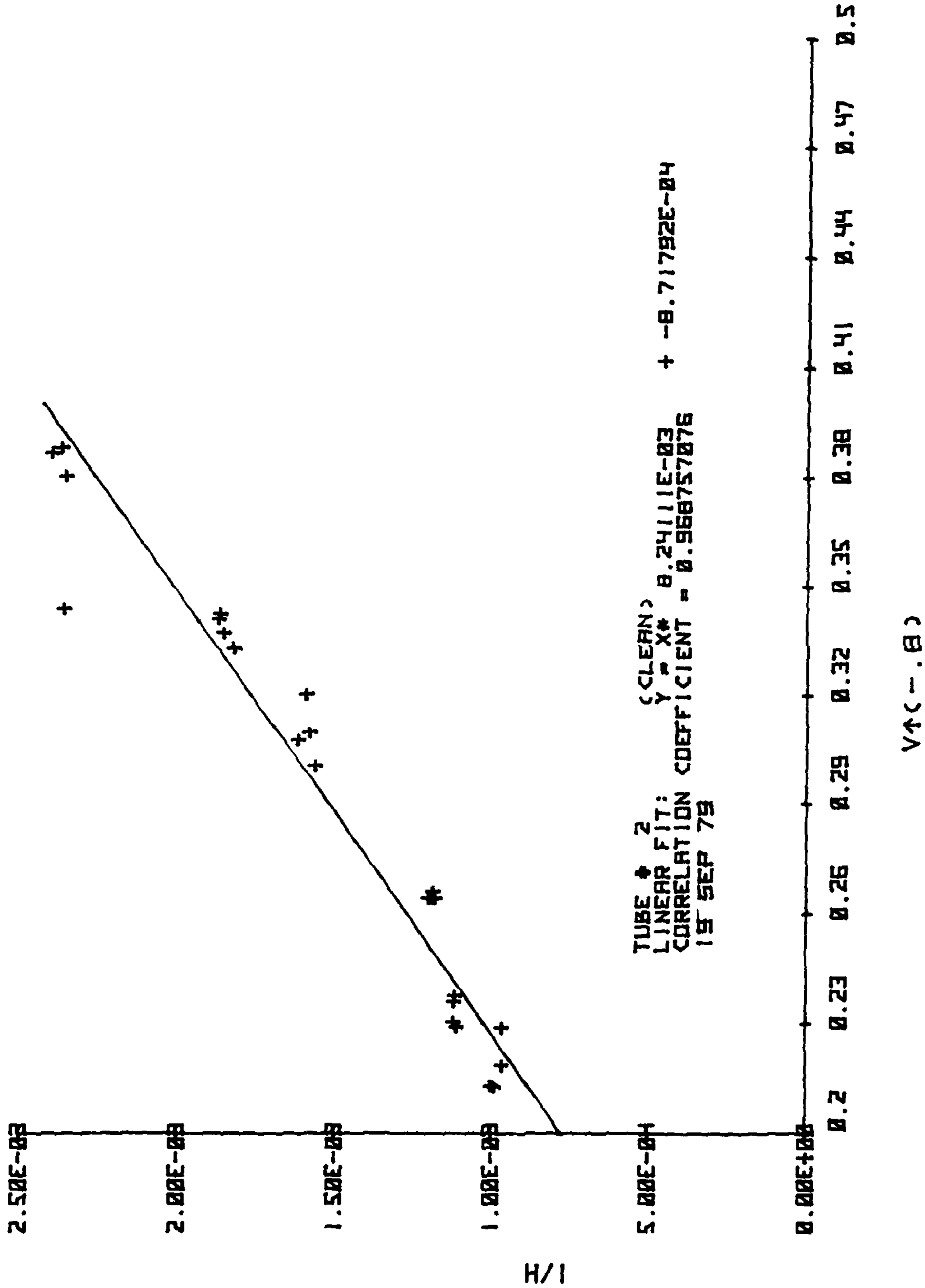
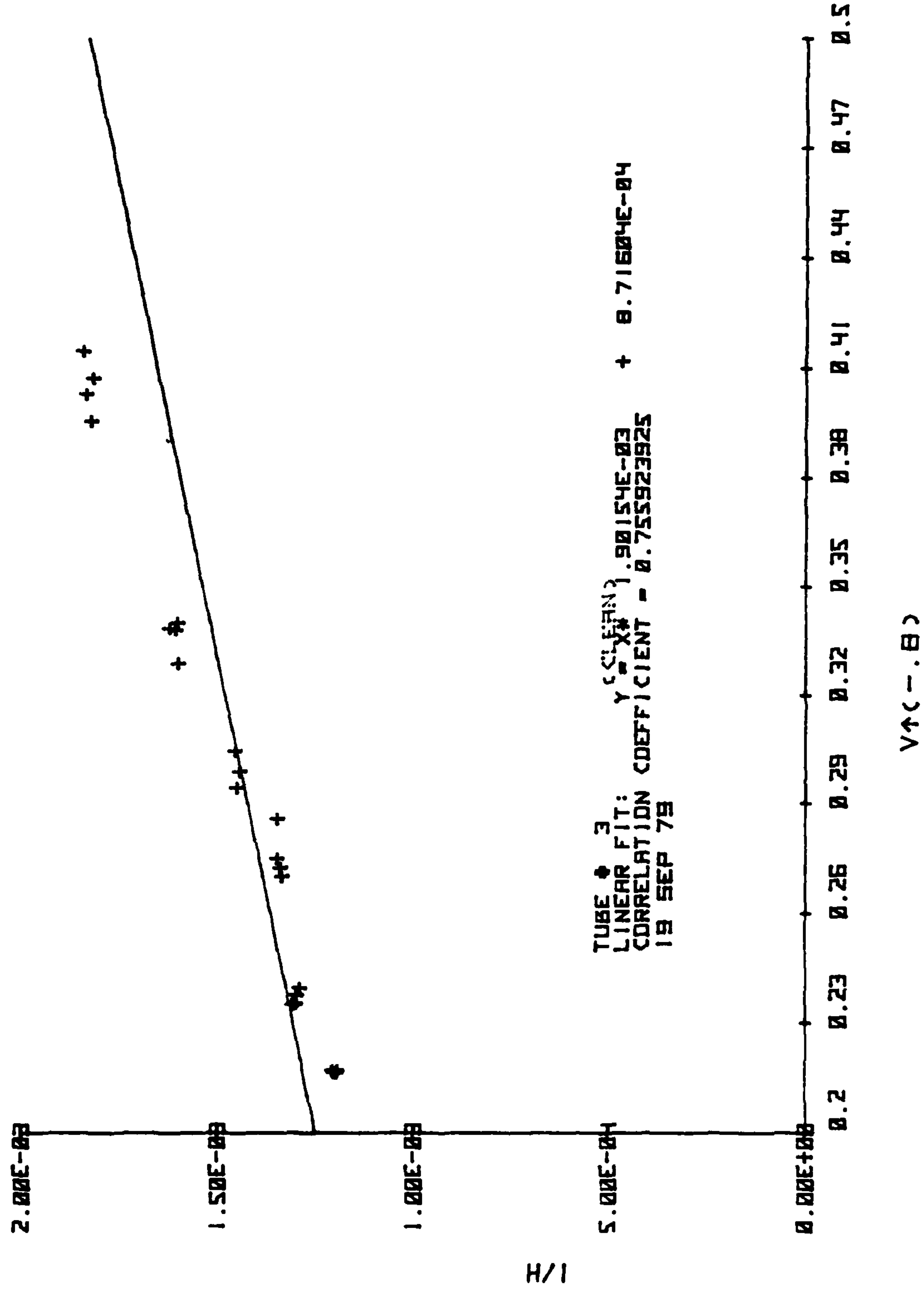

TUBE # 2 (CLEAN)
LINEAR FIT: Y = X* 0.24111E-03 + -0.71792E-04
CORRELATION COEFFICIENT = 0.968757076
19 SEP 79
H/I
2.50E-03
2.00E-03
1.50E-03
1.00E-03
5.00E-04
0.00E+00
V↑(-.8)
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-60



TUBE # 3
LINEAR FIT: Y = X* 1.90154E-03 + 8.71604E-04
CORRELATION COEFFICIENT = 0.755923925
19 SEP 79
H/I
2.00E-03
1.50E-03
1.00E-03
5.00E-04
0.00E+00
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-61

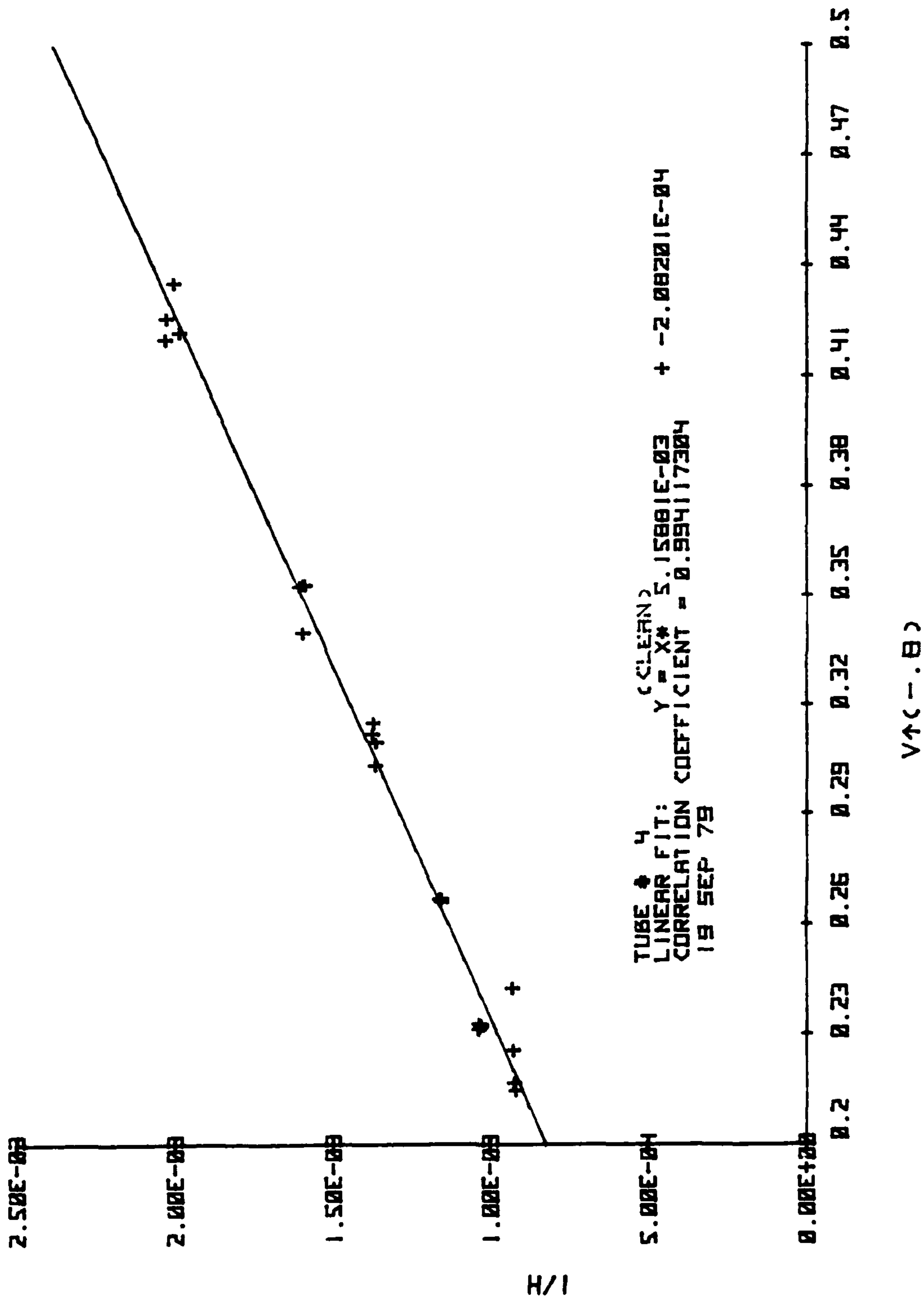

TUBE # 4 (CLEAN)
LINEAR FIT: Y = X* 5.15881E-03 + -2.08201E-04
CORRELATION COEFFICIENT = 0.994117304
19 SEP 79
H/I
V↑(-.8)
0.00E+00
5.00E-04
1.00E-03
1.50E-03
2.00E-03
2.50E-03
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-62

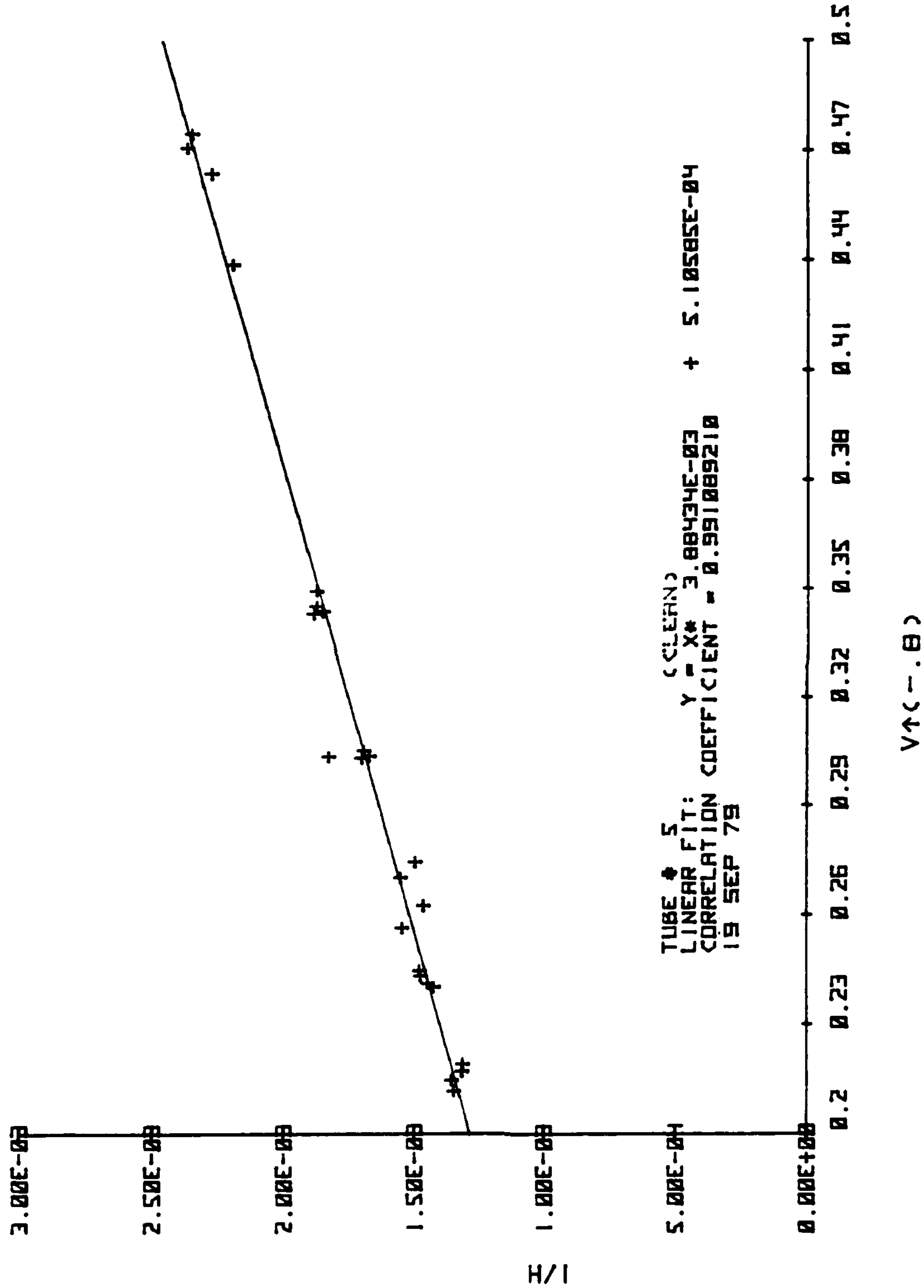

TUBE # 5 (CLEAN)
LINEAR FIT: Y = X* 3.88434E-03 + 5.10585E-04
CORRELATION COEFFICIENT = 0.99108921
19 SEP 79
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)
0.00E+00
5.00E-04
1.00E-03
1.50E-03
2.00E-03
2.50E-03
3.00E-03
H/I

FIGURE B-63

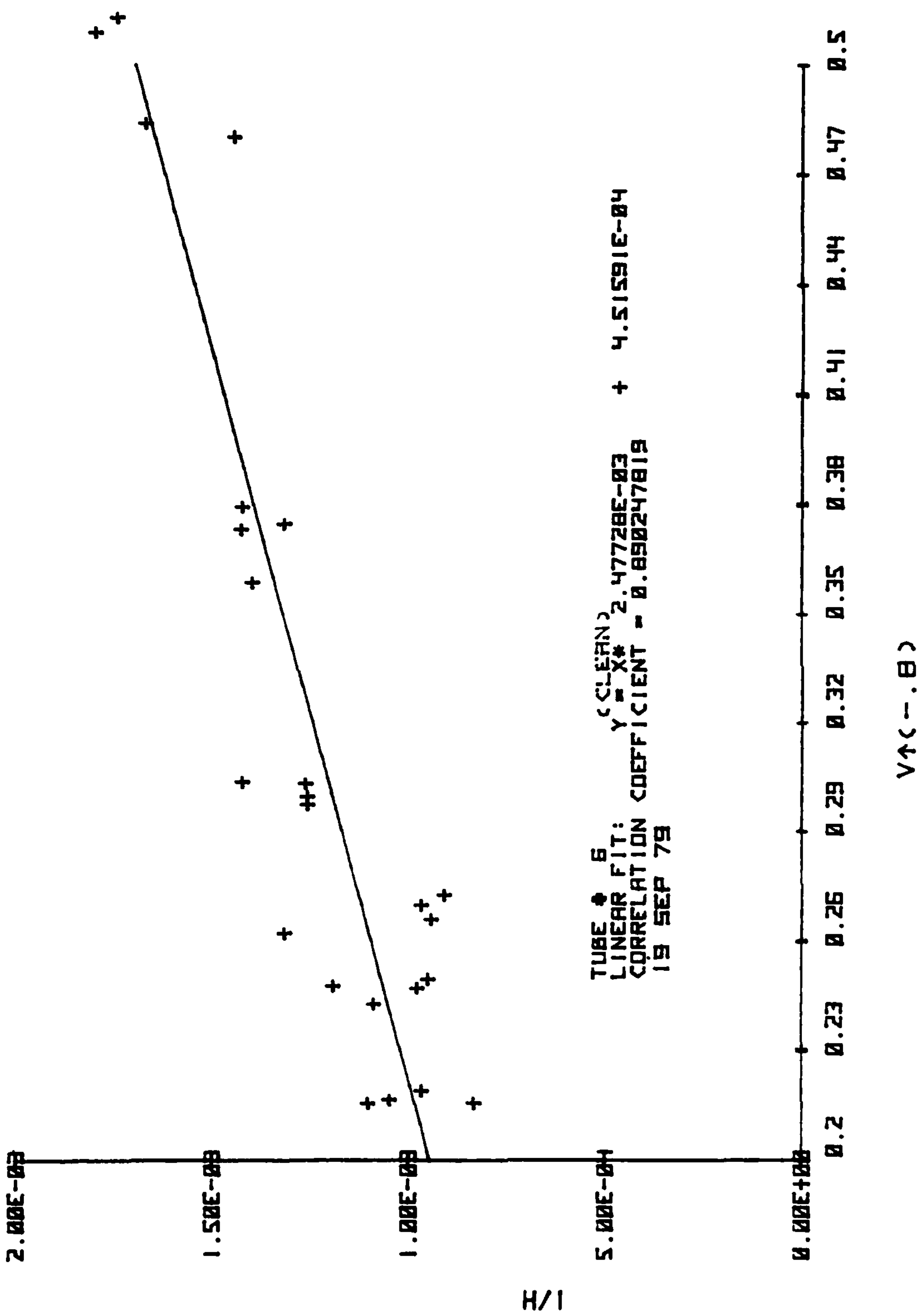

TUBE # 6 (CLEAN)
LINEAR FIT: Y = X* 2.47728E-03 + 4.51591E-04
CORRELATION COEFFICIENT = 0.890247819
19 SEP 79
H/I
V↑(-.8)
0.00E+00
5.00E-04
1.00E-03
1.50E-03
2.00E-03
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-64

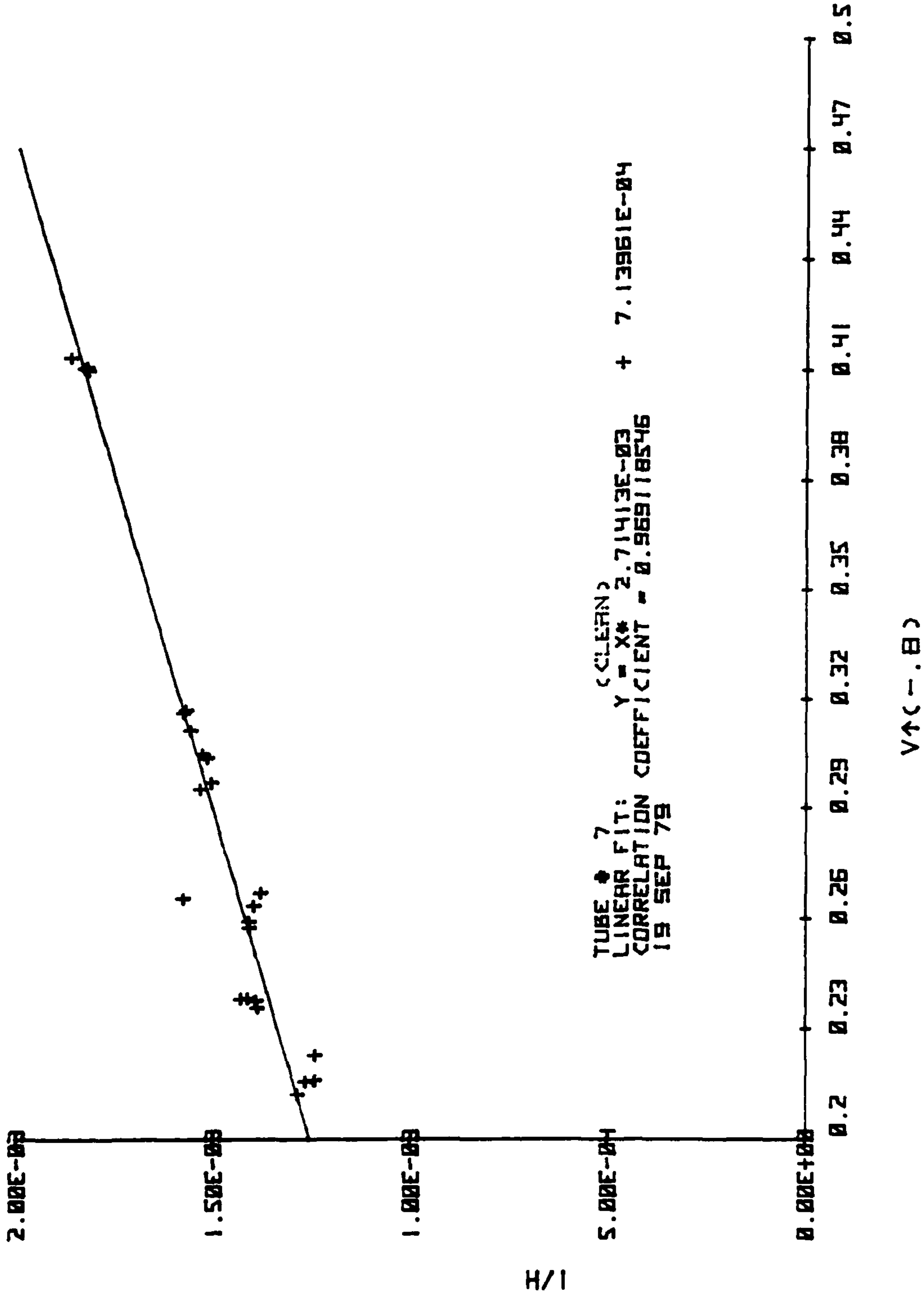

TUBE # 7 (CLEAN)
LINEAR FIT: Y = X* 2.71413E-03 + 7.13961E-04
CORRELATION COEFFICIENT = 0.969118546
19 SEP 79
H/I
2.00E-03
1.50E-03
1.00E-03
5.00E-04
0.00E+00
V↑(-.8)
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-65

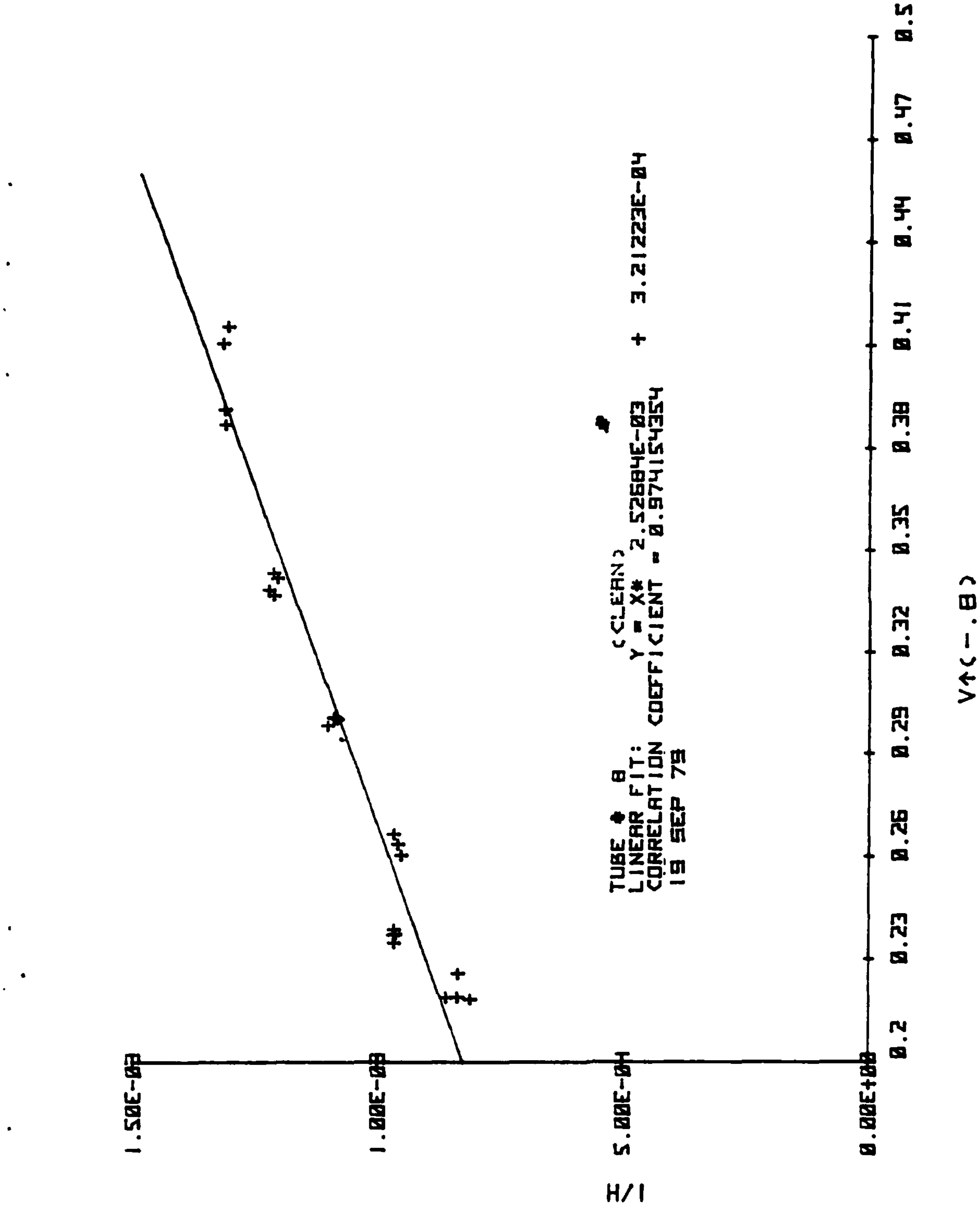

TUBE # 8 (CLEAN)
LINEAR FIT: Y = X* 2.52684E-03 + 3.21223E-04
CORRELATION COEFFICIENT = 0.974154354
19 SEP 79
1.50E-03
1.00E-03
5.00E-04
0.00E+00
H/I
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-66

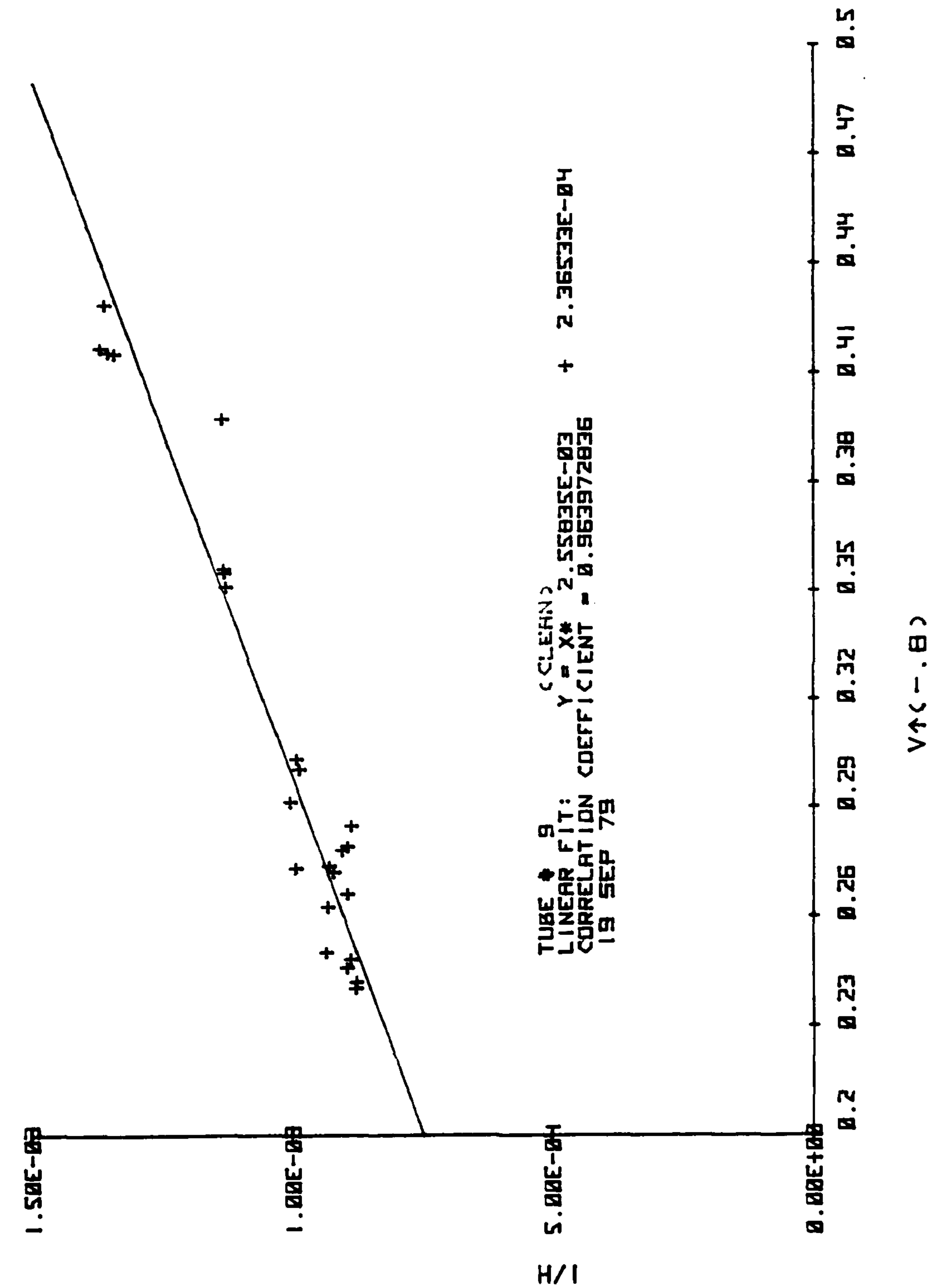

TUBE # 9 (CLEAN)
LINEAR FIT: Y = X* 2.55835E-03 + 2.36533E-04
CORRELATION COEFFICIENT = 0.963972836
19 SEP 79
1/H
V↑(-.8)
0.00E+00
5.00E-04
1.00E-03
1.50E-03
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-67

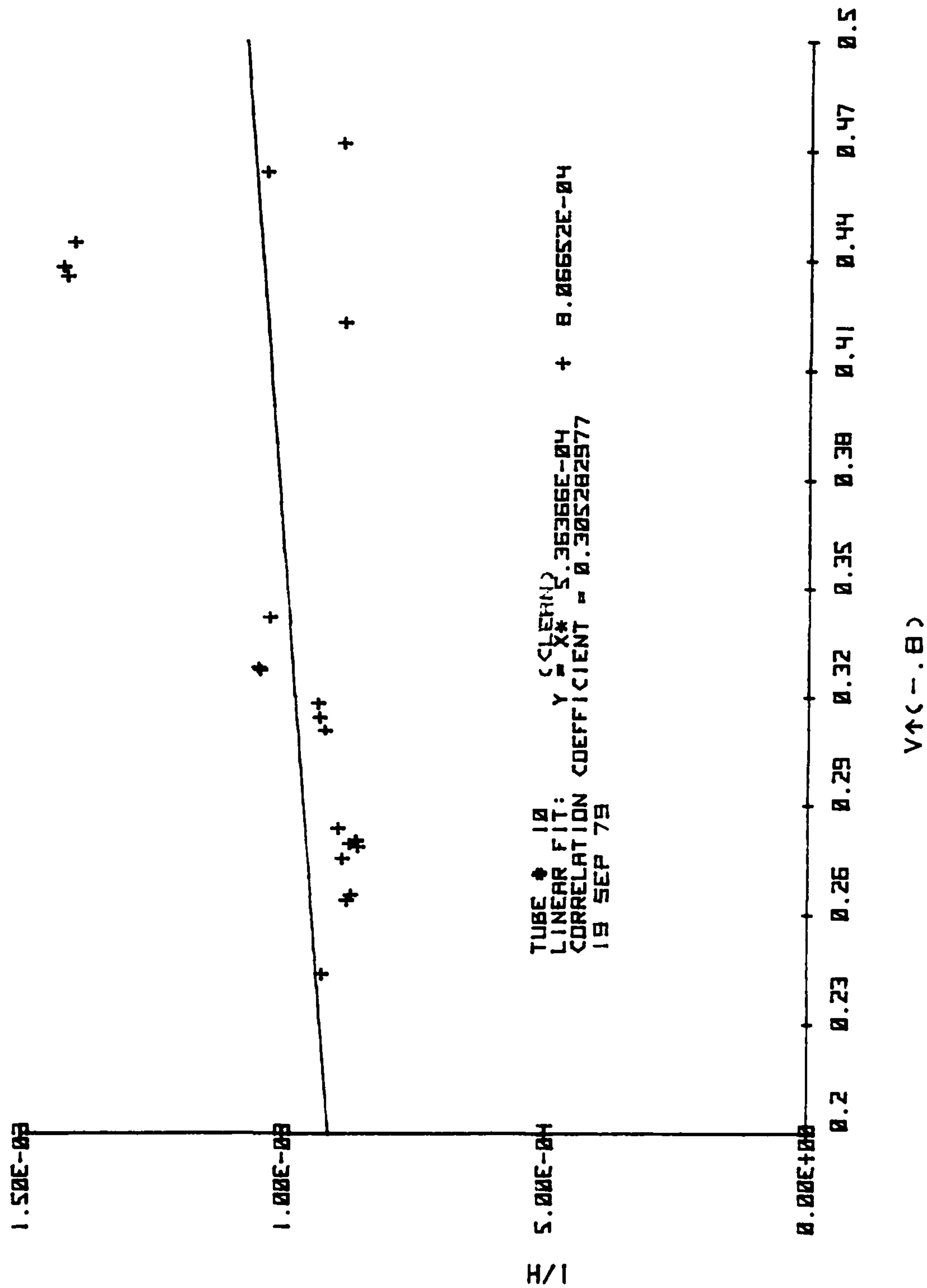

TUBE # 10 (CLEAN)
LINEAR FIT: Y = X* 5.36366E-04 + 0.06652E-04
CORRELATION COEFFICIENT = 0.305282977
19 SEP 79
H/I
V↑(-.8)
1.50E-03
1.00E-03
5.00E-04
0.00E+00
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-68

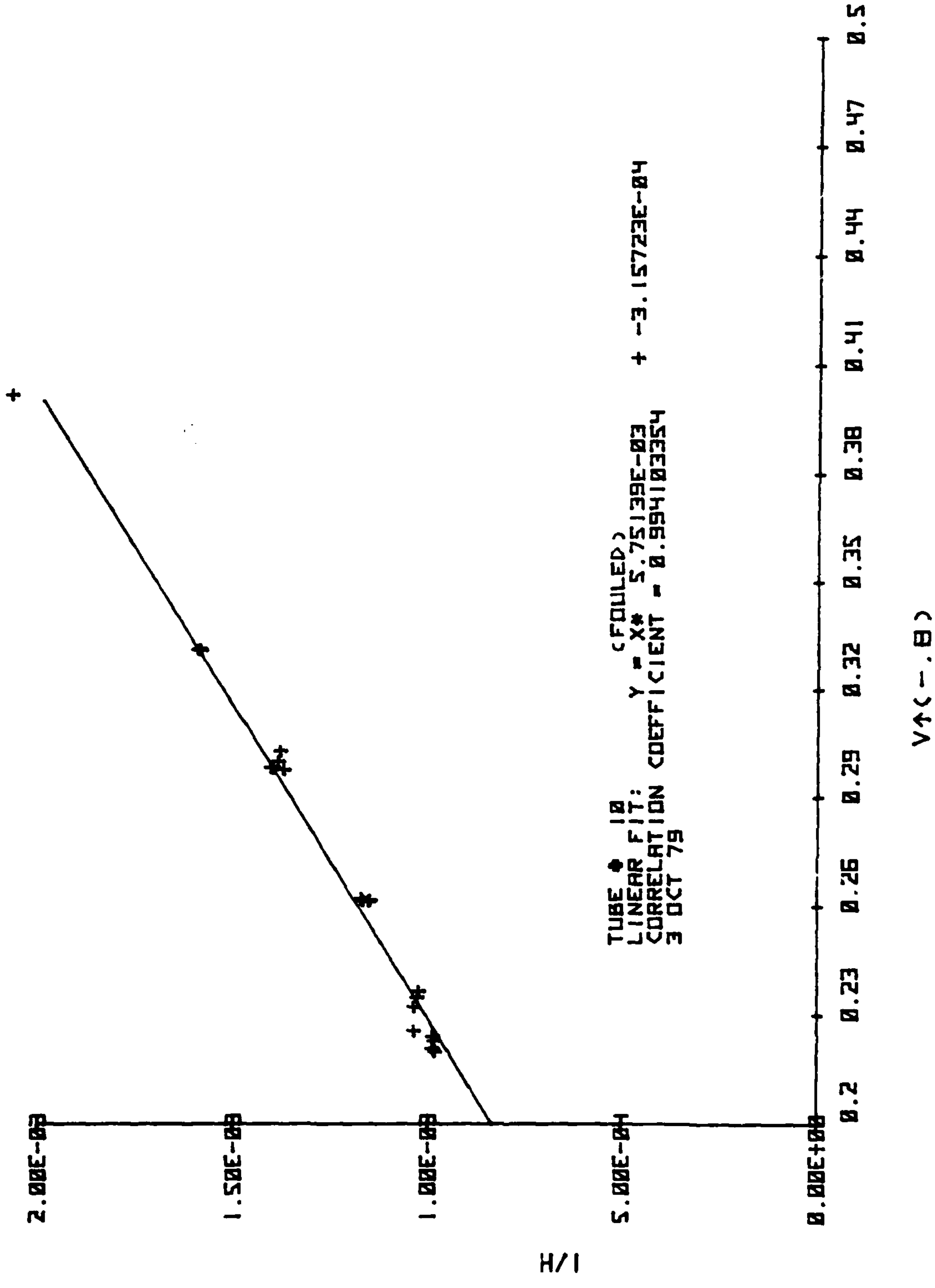

TUBE # 10 (FOULED)
LINEAR FIT: Y = X* 5.75139E-03 + -3.15723E-04
CORRELATION COEFFICIENT = 0.994103354
3 OCT 79
H/I
V↑(-.8)
2.00E-03
1.50E-03
1.00E-03
5.00E-04
0.00E+00
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-69

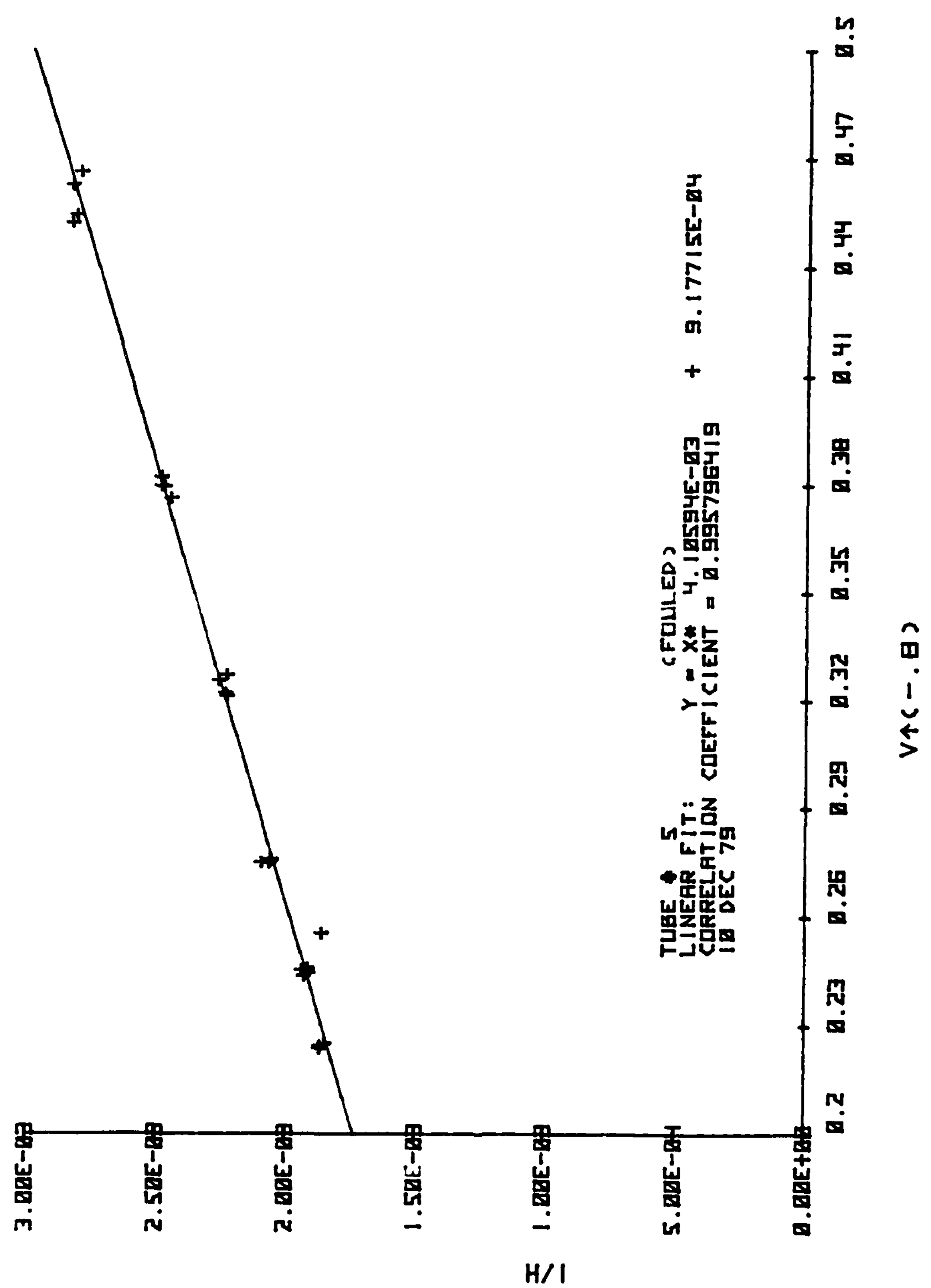

TUBE # 5 (FOULED)
LINEAR FIT: Y = X* 4.10594E-03 + 9.17715E-04
CORRELATION COEFFICIENT = 0.995796419
10 DEC 79
H/I
V↑(-.8)
0.00E+00
5.00E-04
1.00E-03
1.50E-03
2.00E-03
2.50E-03
3.00E-03
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-70

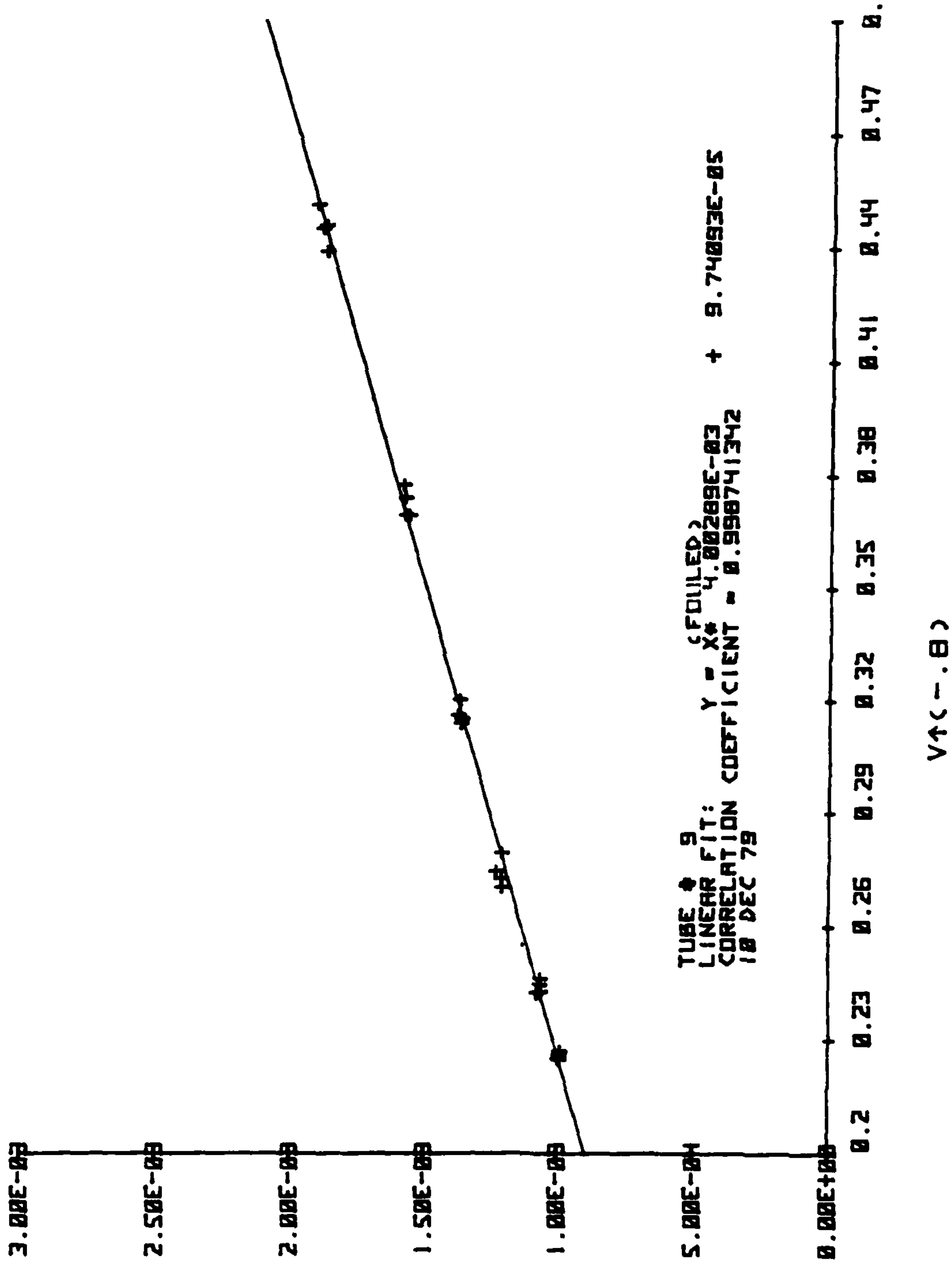

TUBE # 9 (FOULED)
LINEAR FIT: Y = X* 4.00289E-03 + 9.74093E-05
CORRELATION COEFFICIENT = 0.998741342
10 DEC 79
H/I
V↑(-.8)
3.00E-03
2.50E-03
2.00E-03
1.50E-03
1.00E-03
5.00E-04
0.00E+00
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-71

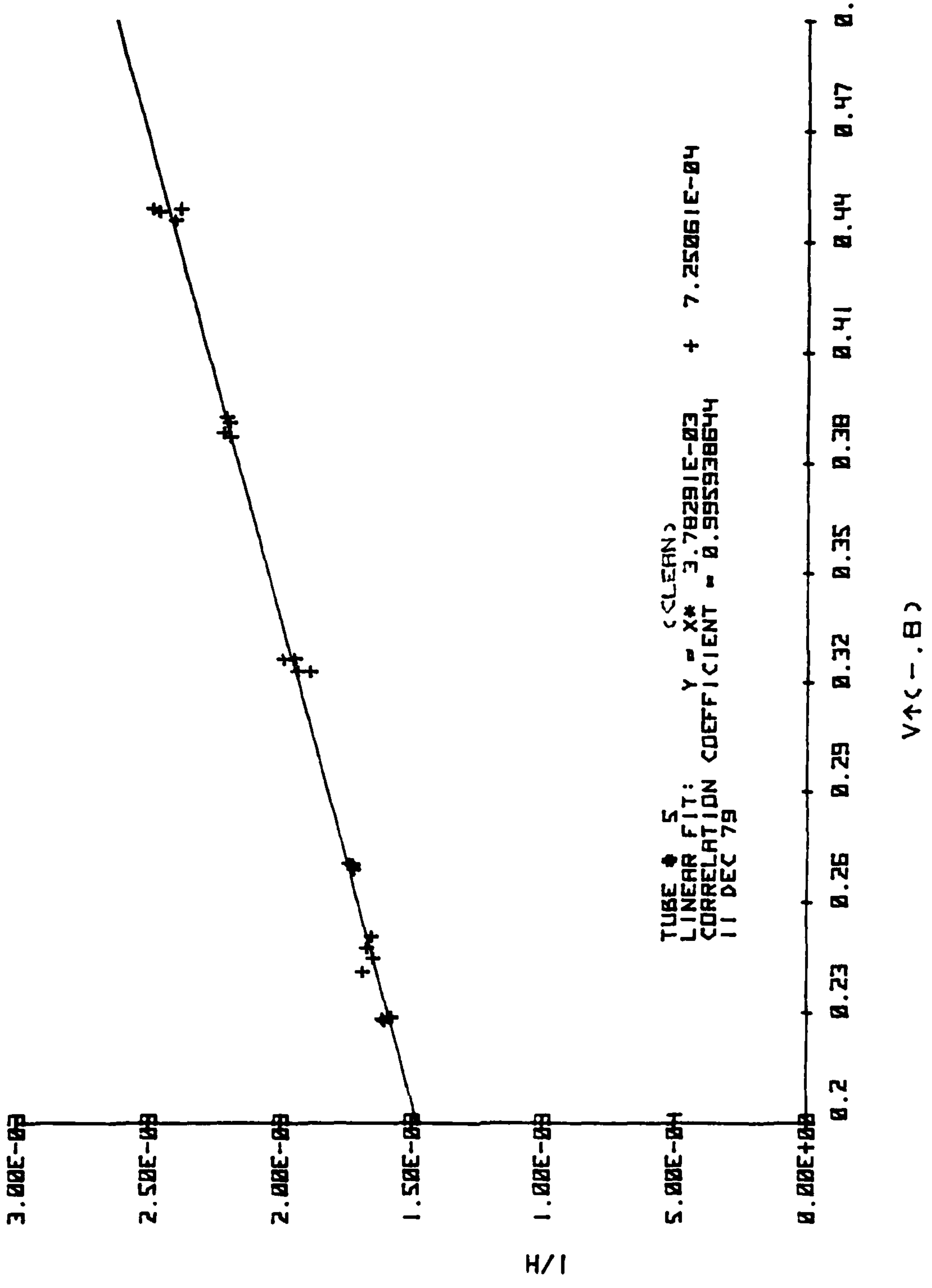
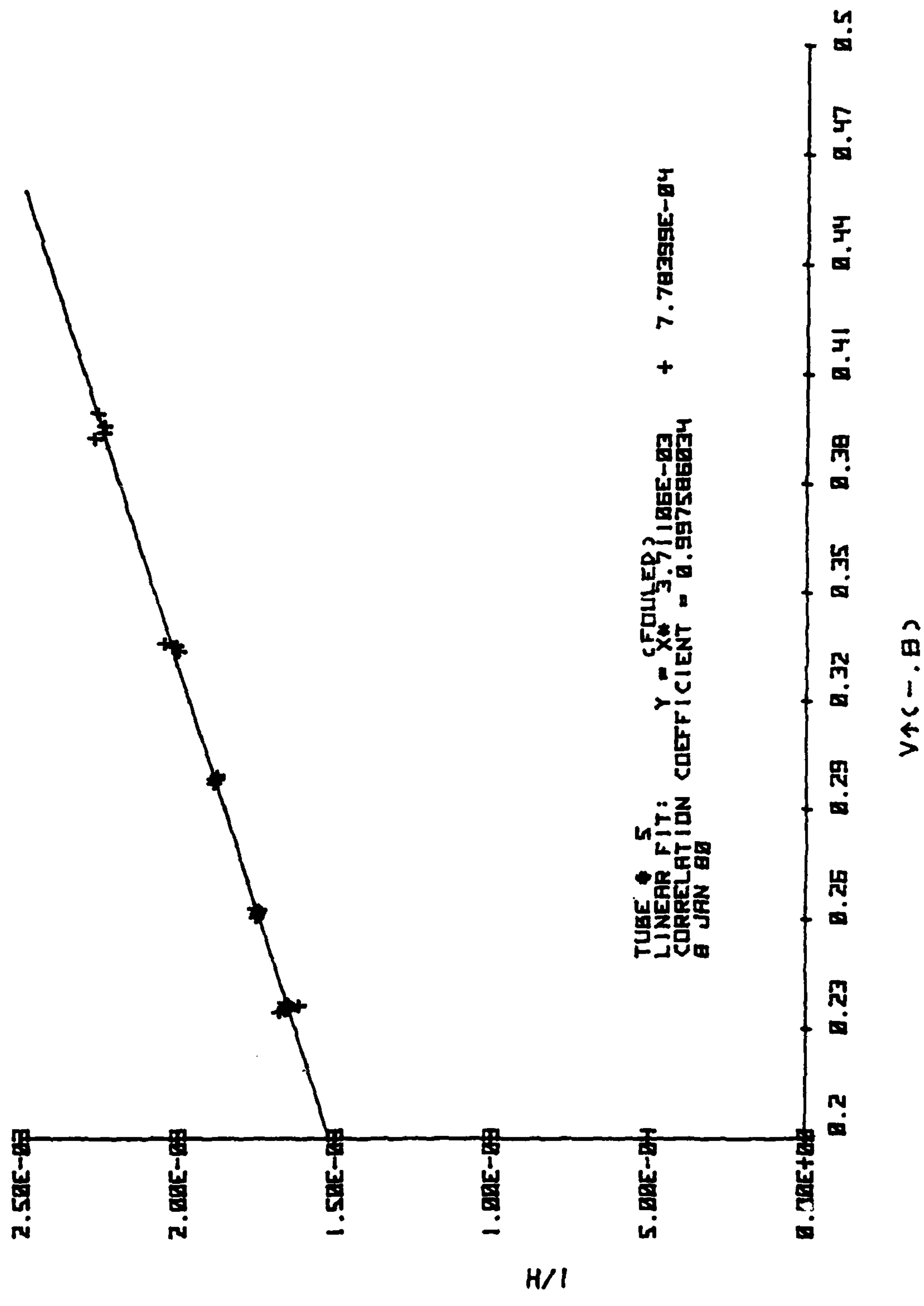

TUBE # 5 (CLEAN)
LINEAR FIT: Y = X* 3.78291E-03 + 7.25061E-04
CORRELATION COEFFICIENT = 0.995938644
11 DEC 79
1/H
3.00E-03
2.50E-03
2.00E-03
1.50E-03
1.00E-03
5.00E-04
0.00E+00
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-72



TUBE # 5
LINEAR FIT: Y = X* 3.71106E-03 + 7.78399E-04 (FOWLER)
CORRELATION COEFFICIENT = 0.997586034
8 JAN 80
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)
0.00E+00
5.00E-04
1.00E-03
1.50E-03
2.00E-03
2.50E-03
I/V

FIGURE B-73

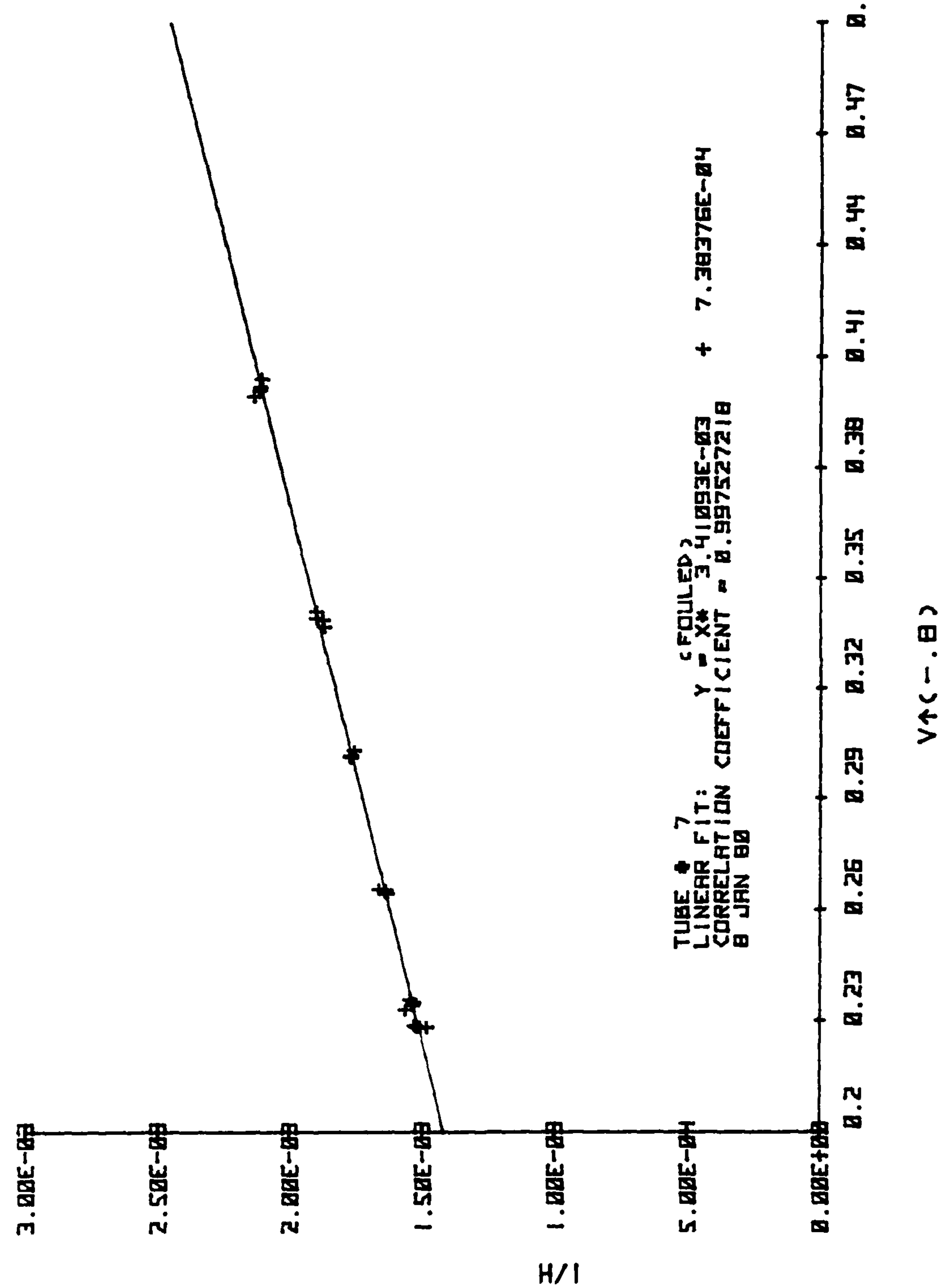

TUBE # 7 (FOULED)
LINEAR FIT: Y = X* 3.41093E-03 + 7.38376E-04
CORRELATION COEFFICIENT = 0.997527218
8 JAN 80
3.00E-03
2.50E-03
2.00E-03
1.50E-03
1.00E-03
5.00E-04
0.00E+00
H/I
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-74

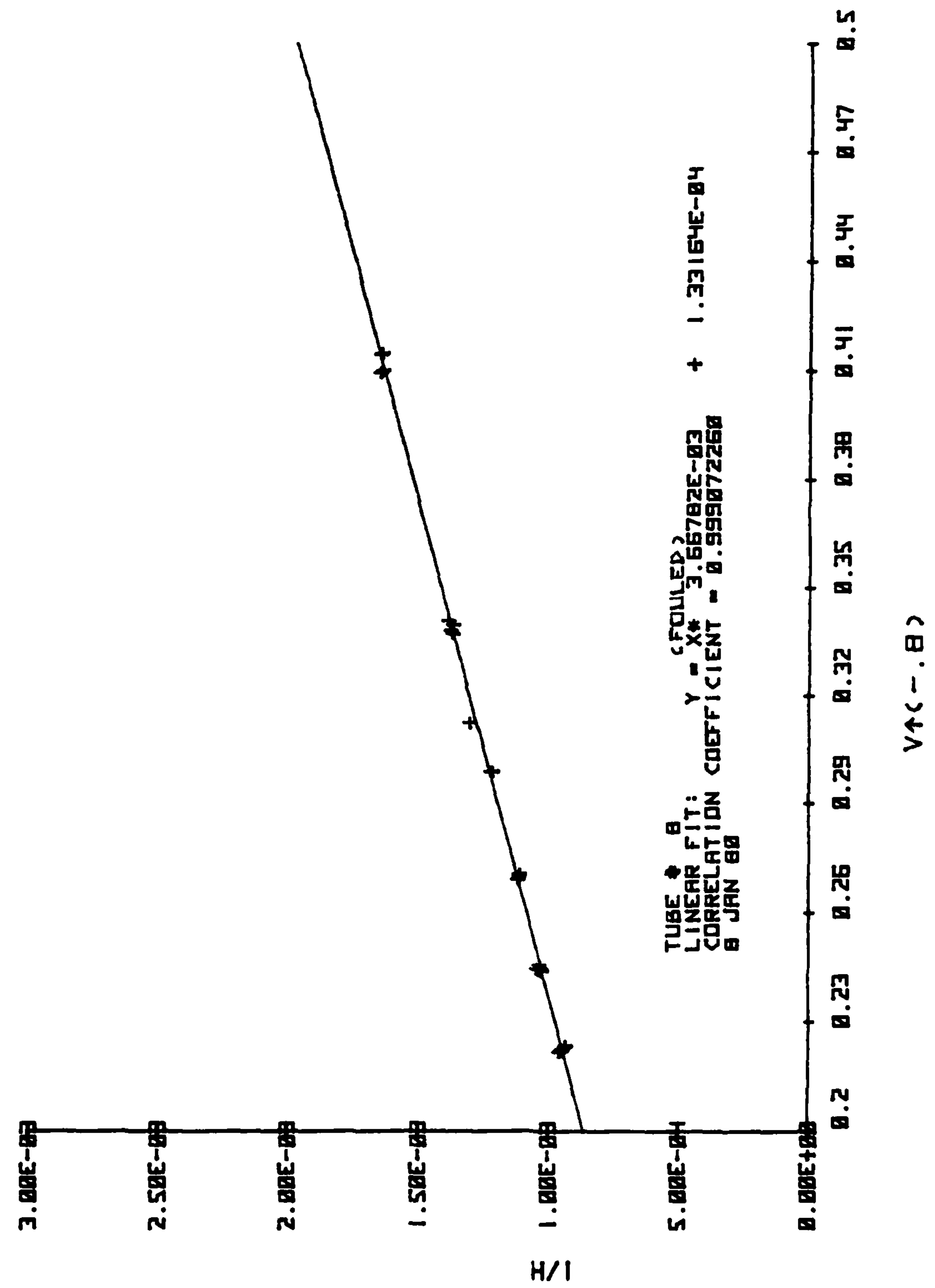

TUBE # 8
LINEAR FIT: Y = X* 3.66782E-03 + 1.33164E-04
(FOULED)
CORRELATION COEFFICIENT = 0.99907226
8 JAN 80
V↑(-.8)
1/H
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
0.00E+00
5.00E-04
1.00E-03
1.50E-03
2.00E-03
2.50E-03
3.00E-03

FIGURE B-75

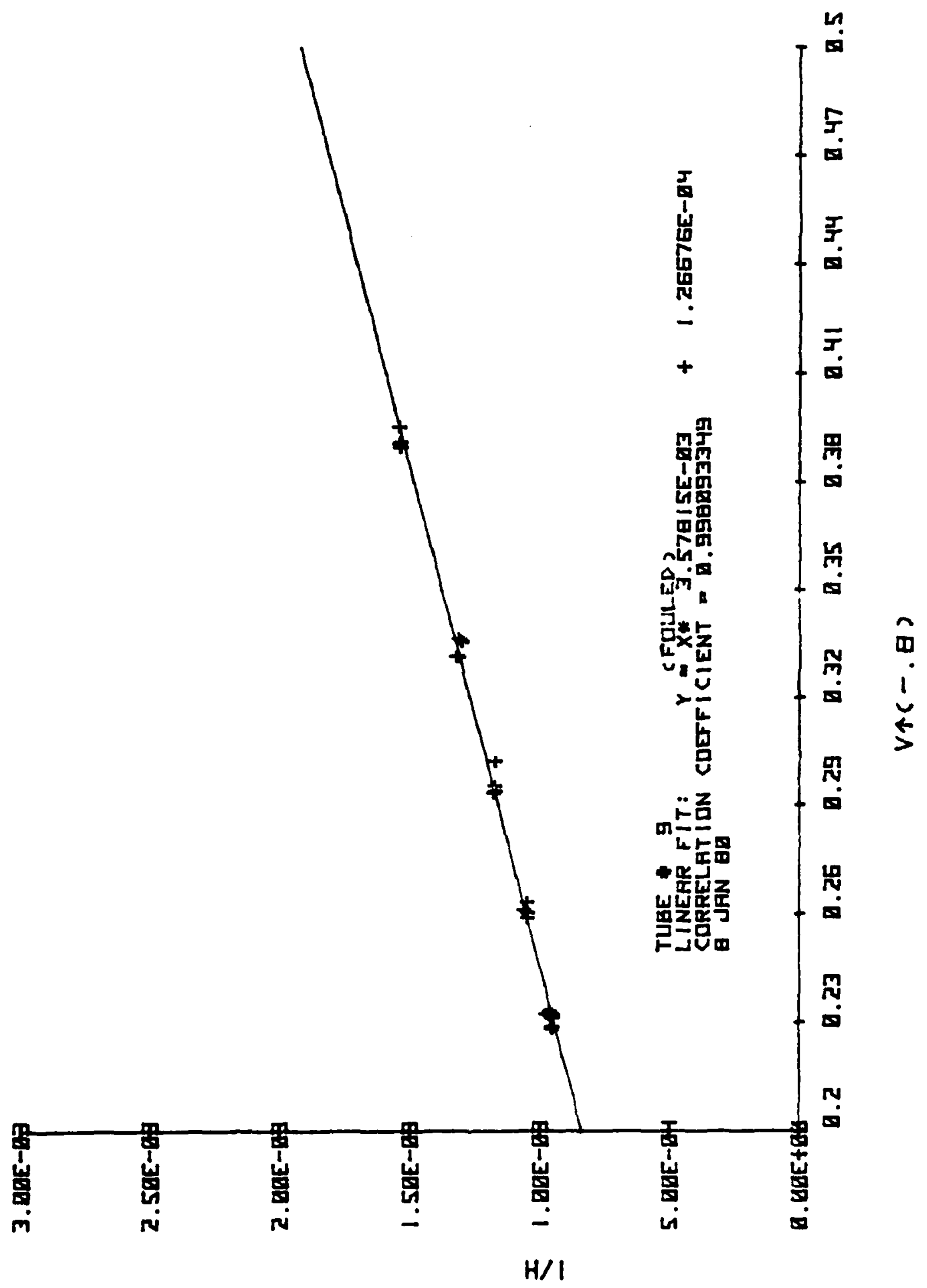

TUBE # 9 (FOULED)
LINEAR FIT: Y = X* 3.57815E-03 + 1.26676E-04
CORRELATION COEFFICIENT = 0.998093349
8 JAN 80
3.00E-03
2.50E-03
2.00E-03
1.50E-03
1.00E-03
5.00E-04
0.00E+00
H/I
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-76

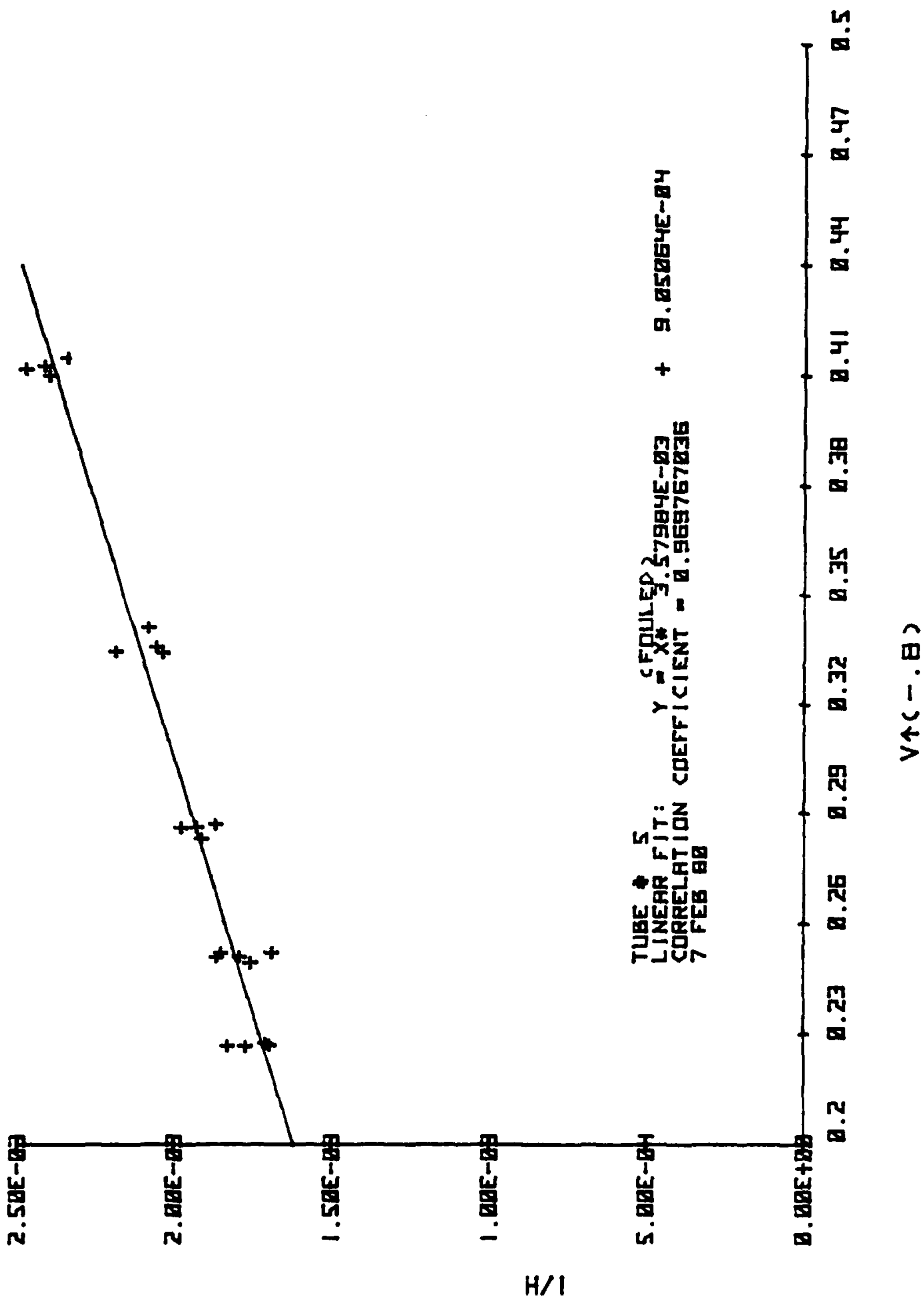

TUBE # 5 (FOULED)
LINEAR FIT: Y = X* 3.57984E-03 + 9.05064E-04
CORRELATION COEFFICIENT = 0.969767036
7 FEB 80
H/I
2.50E-03
2.00E-03
1.50E-03
1.00E-03
5.00E-04
0.00E+00
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-77

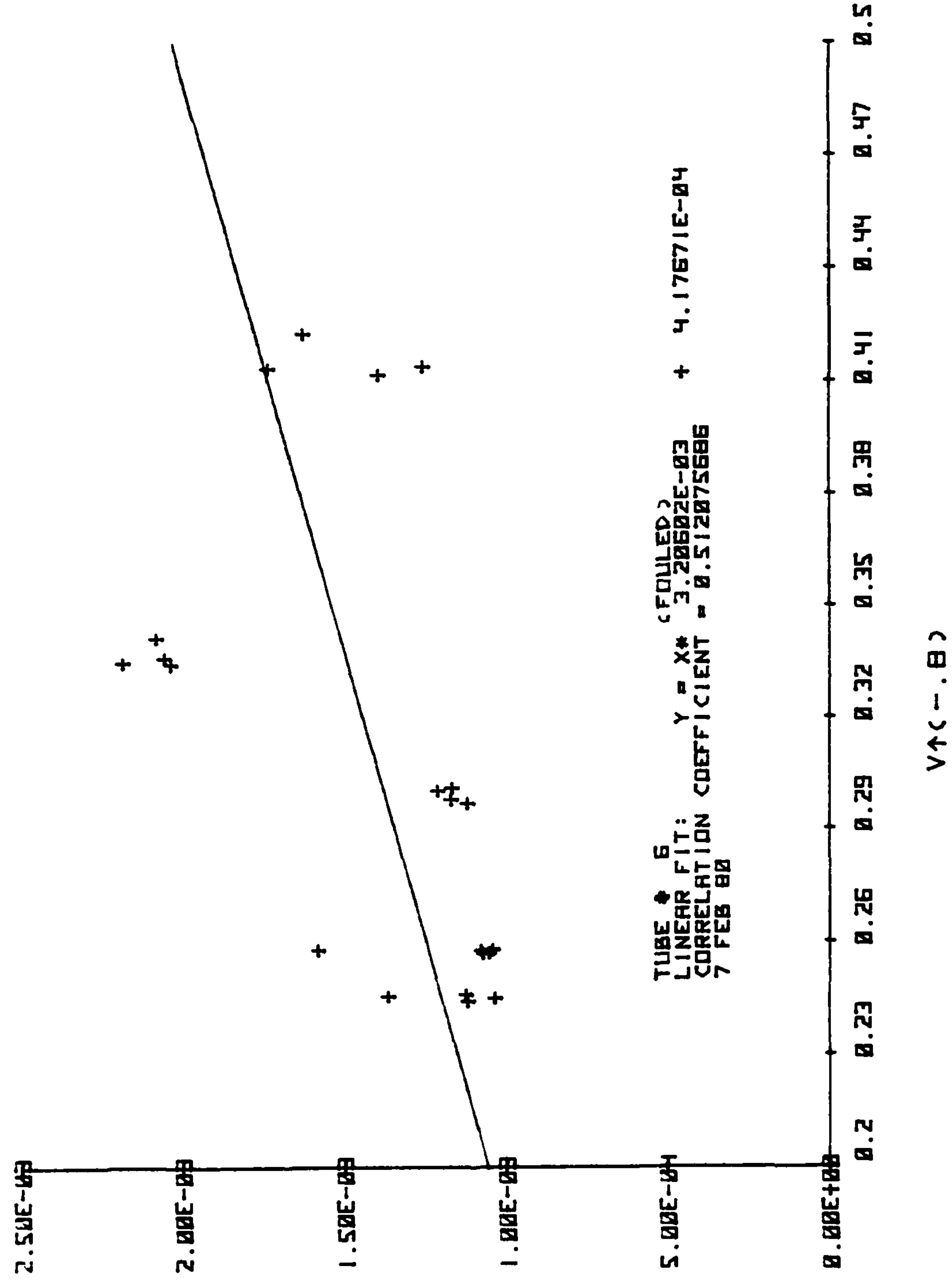

TUBE # 6
LINEAR FIT: Y = X* 3.20602E-03 + 4.17671E-04 (FOULED)
CORRELATION COEFFICIENT = 0.512075686
7 FEB 80
H/I
V↑(-.8)
0.00E+00
5.00E-04
1.00E-03
1.50E-03
2.00E-03
2.50E-03
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-78

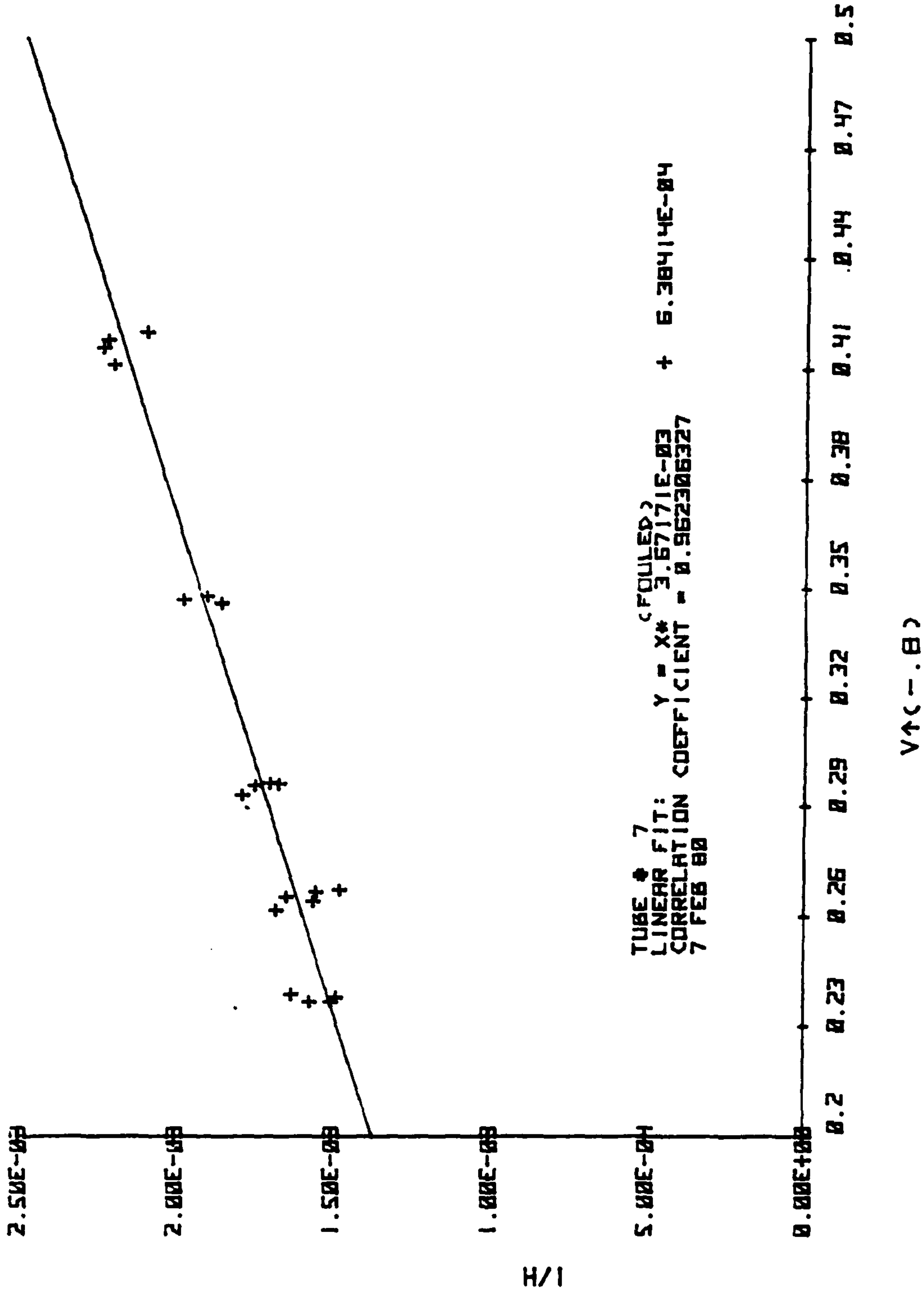

TUBE # 7
LINEAR FIT: Y = X* 3.67171E-03 + 6.38414E-04
(FOULED)
CORRELATION COEFFICIENT = 0.962306327
7 FEB 80
H/I
V↑(-.8)
2.50E-03
2.00E-03
1.50E-03
1.00E-03
5.00E-04
0.00E+00
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-79

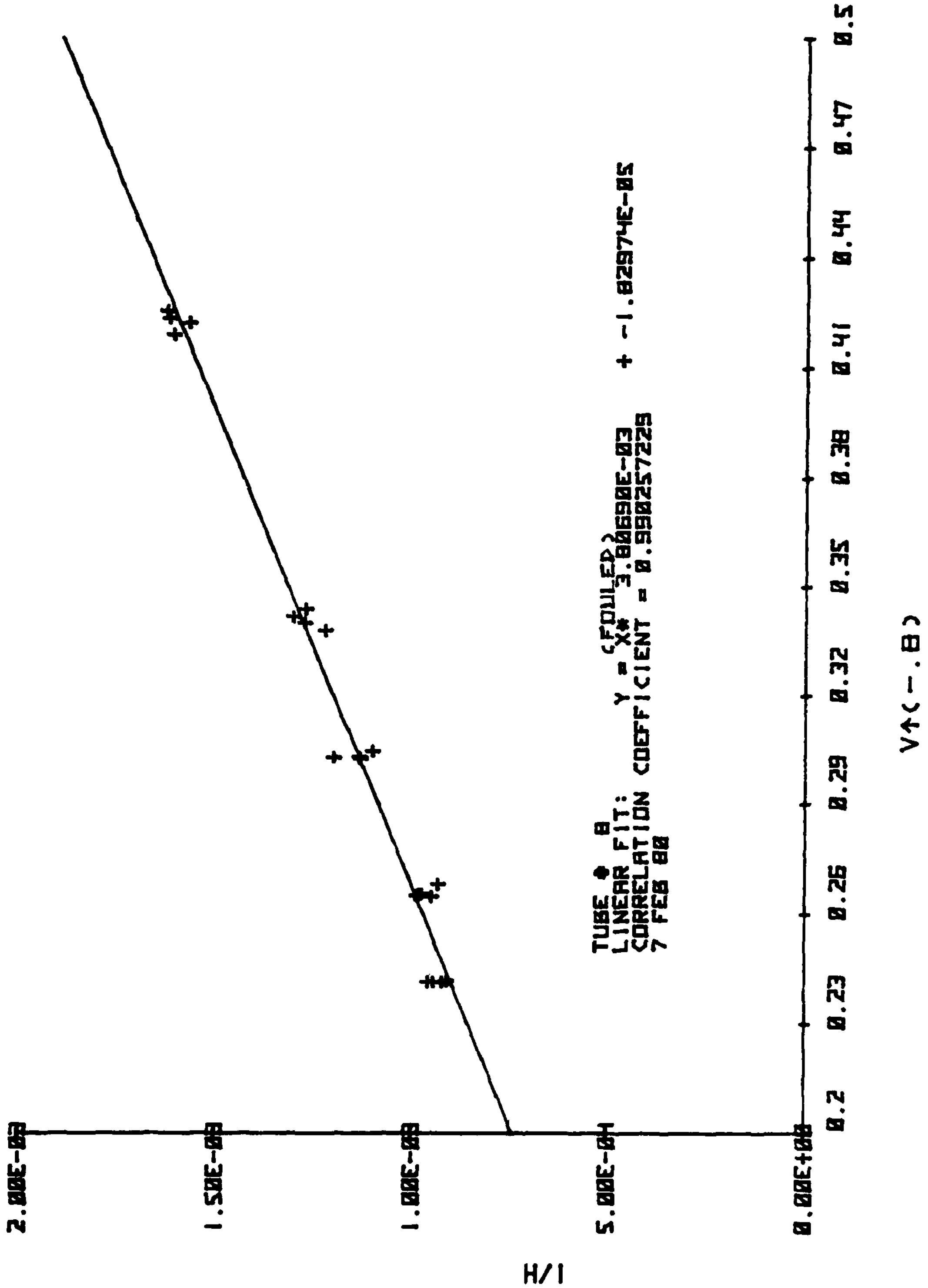

TUBE # 8
LINEAR FIT: Y = (FOULED) X* 3.80690E-03 + -1.02974E-05
CORRELATION COEFFICIENT = 0.990257229
7 FEB 80
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)
0.00E+00
5.00E-04
1.00E-03
1.50E-03
2.00E-03
H/I

FIGURE B-80

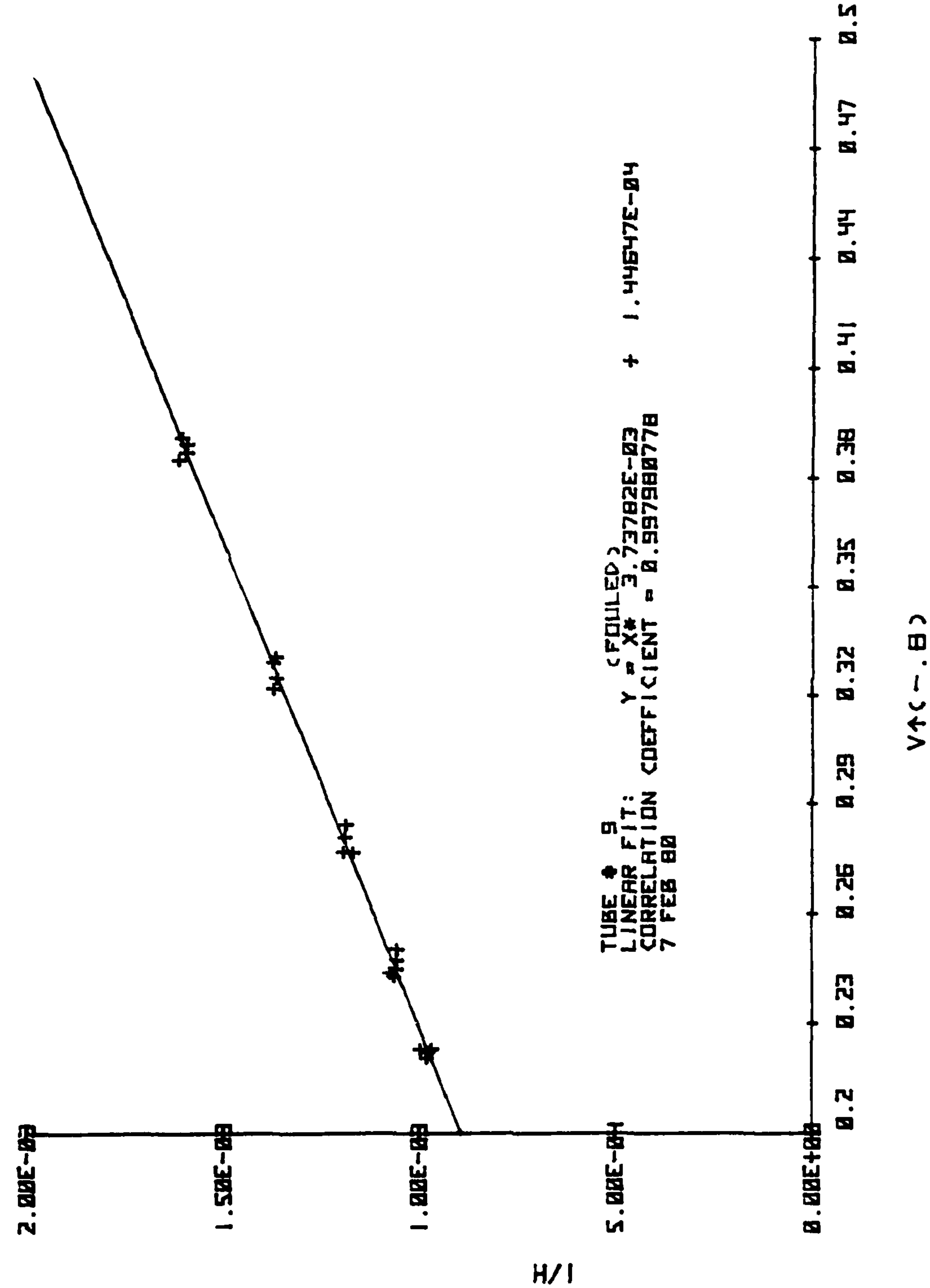

TUBE # 9
LINEAR FIT: (FOULED) Y = X* 3.73782E-03 + 1.44647E-04
CORRELATION COEFFICIENT = 0.997980778
7 FEB 80
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
0.00E+00
5.00E-04
1.00E-03
1.50E-03
2.00E-03
H/I
V↑(-.8)

FIGURE B-81

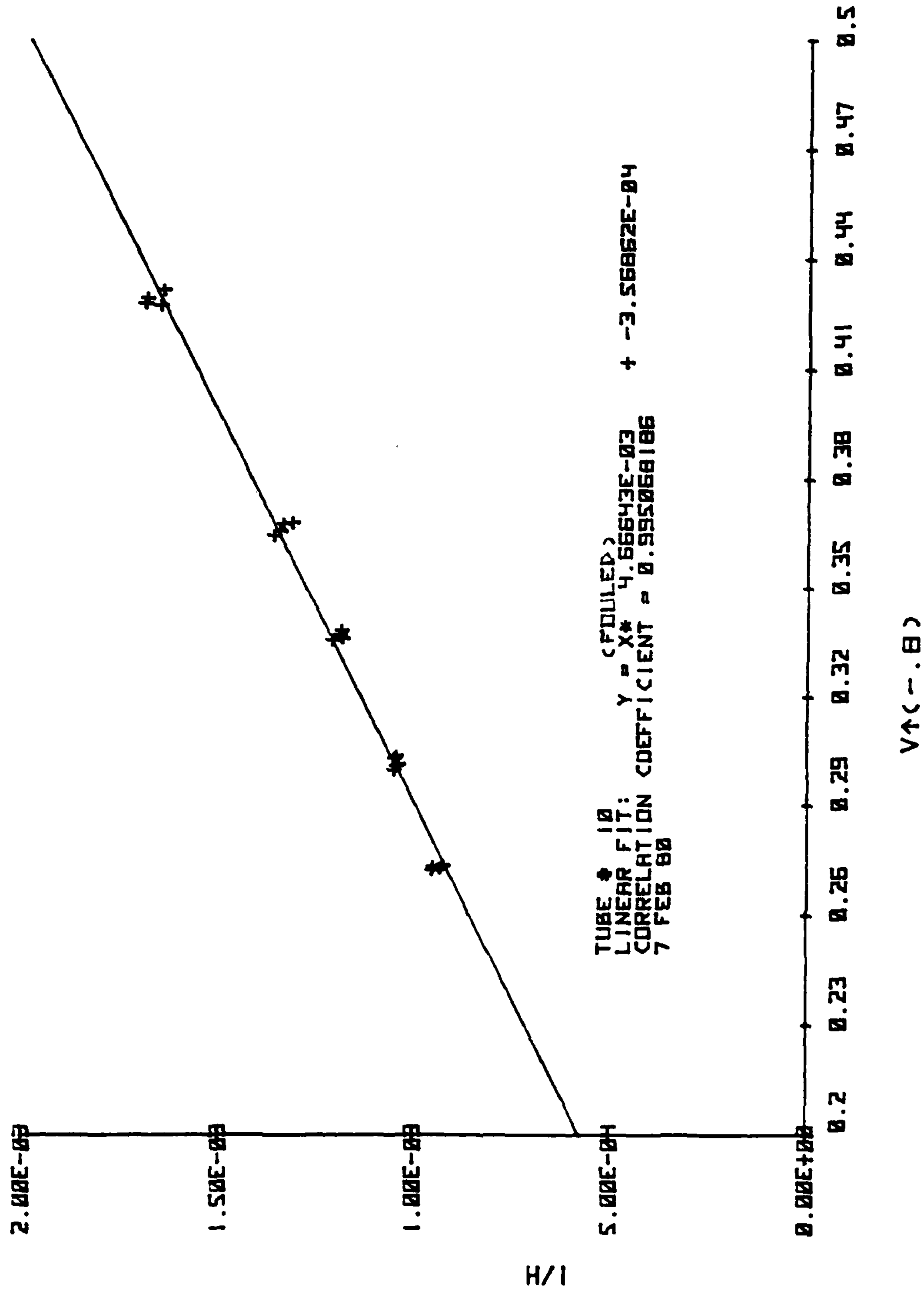

TUBE # 10 (FOULED)
LINEAR FIT: Y = X* 4.66643E-03 + -3.56862E-04
CORRELATION COEFFICIENT = 0.995068186
7 FEB 80
H/I
2.00E-03
1.50E-03
1.00E-03
5.00E-04
0.00E+00
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-82

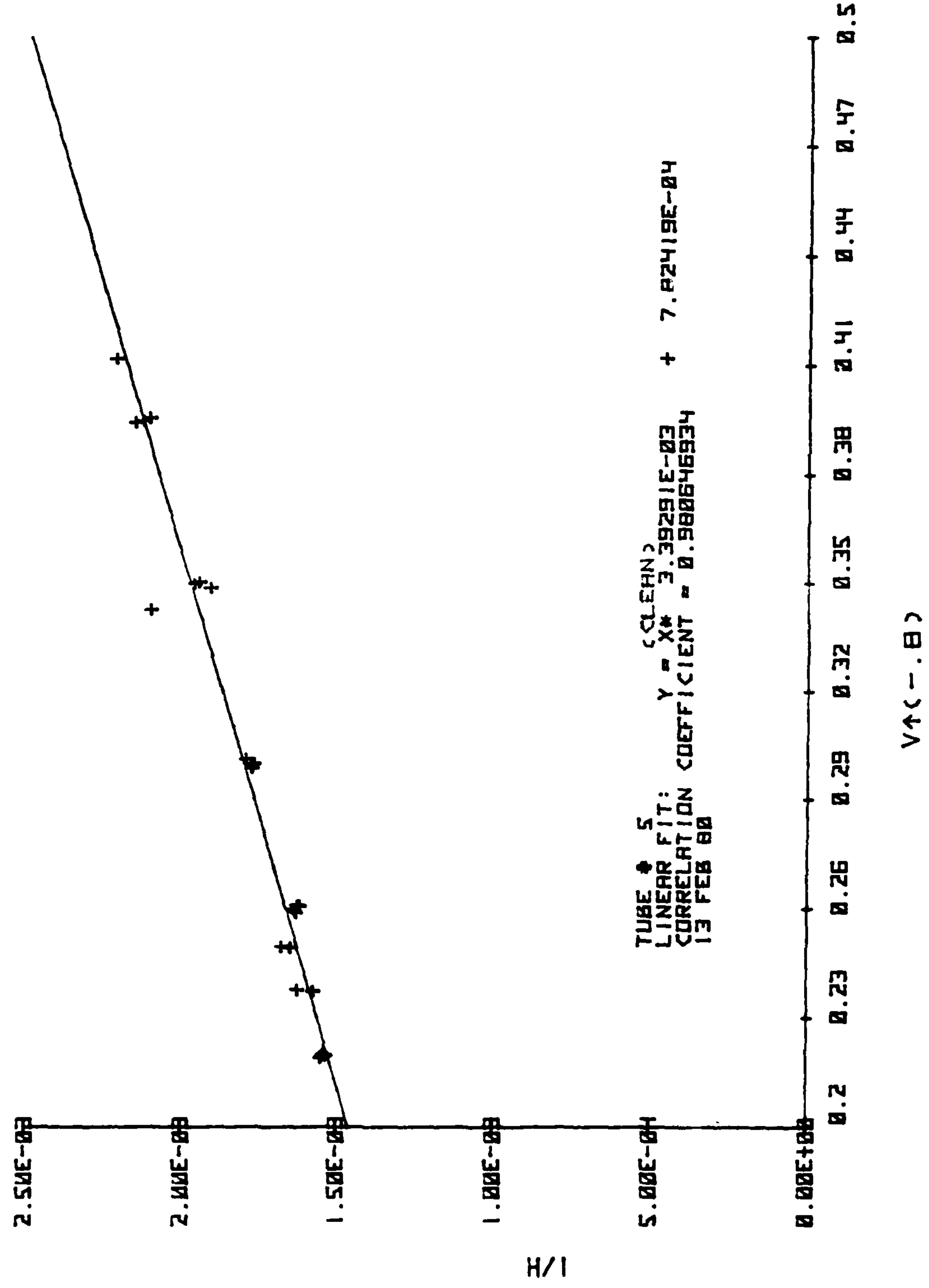

TUBE # 5 (CLEAN)
LINEAR FIT: Y = X* 3.39291E-03 + 7.82419E-04
CORRELATION COEFFICIENT = 0.980646934
13 FEB 80
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)
0.00E+00
5.00E-04
1.00E-03
1.50E-03
2.00E-03
2.50E-03
H/I

FIGURE B-83

AD-A096 343 NAVAL COASTAL SYSTEMS CENTER PANAMA CITY FL F/G 13/1
TEST RESULTS OF HEAT EXCHANGER CLEANING IN SUPPORT OF OCEAN THE--ETC(U)
DEC 80 D F LOTT IAA-ET-78-01-3218
UNCLASSIFIED NCSC-TM-298-80

3 OF 3

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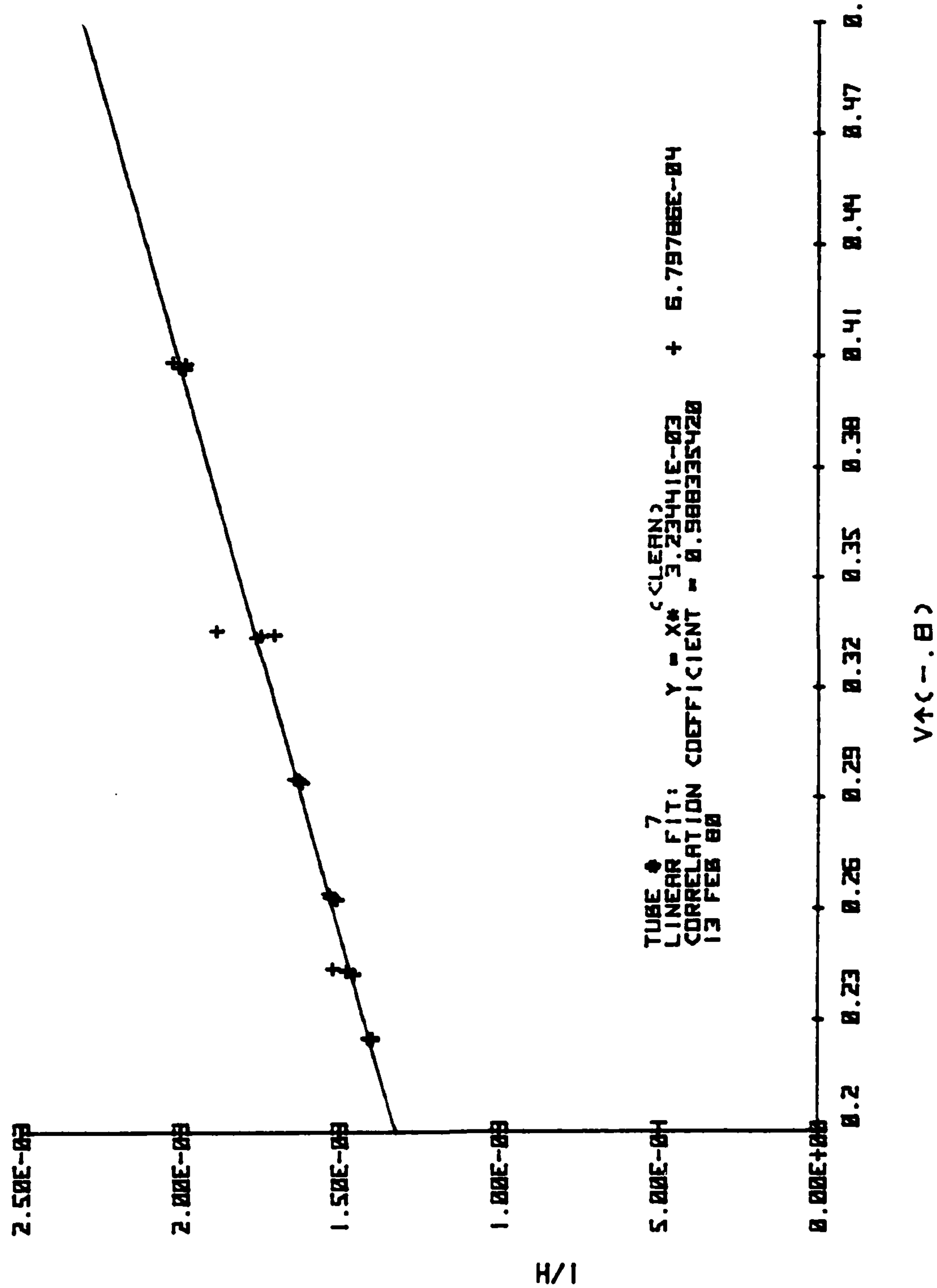

TUBE # 7
LINEAR FIT: Y = X* 3.23441E-03 + 6.79786E-04
(CLEAN)
CORRELATION COEFFICIENT = 0.988335420
13 FEB 80
H/I
V↑(-.8)
2.50E-03
2.00E-03
1.50E-03
1.00E-03
5.00E-04
0.00E+00
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-84

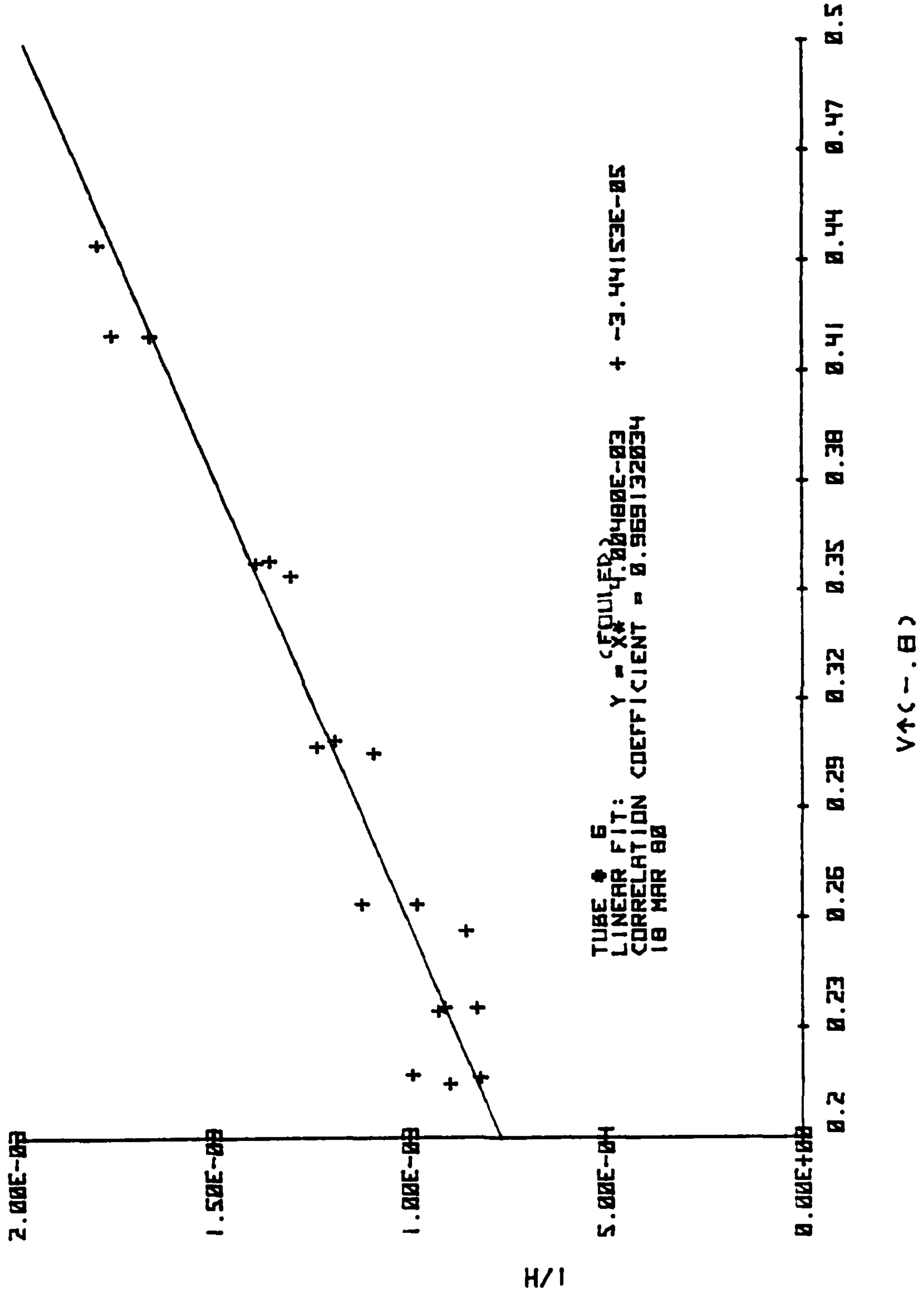

TUBE # 6
LINEAR FIT: Y = 4.00480E-03 X* + -3.44153E-05
CORRELATION COEFFICIENT = 0.969132034
10 MAR 80
2.00E-03
1.50E-03
1.00E-03
5.00E-04
0.00E+00
H/I
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-85

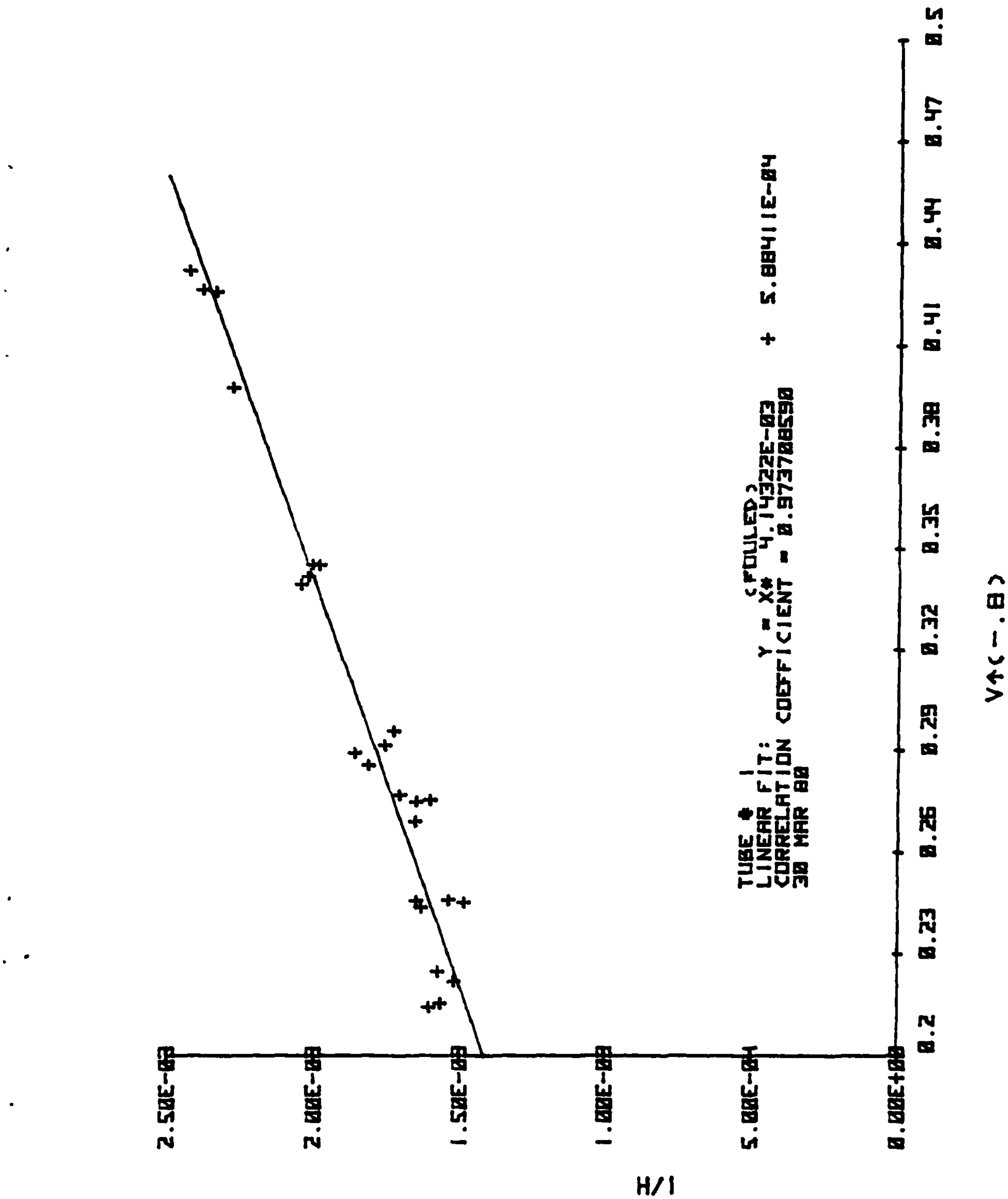

TUBE # 1
LINEAR FIT: Y = X* 4.14322E-03 + 5.88411E-04
(FOULED)
CORRELATION COEFFICIENT = 0.973708590
30 MAR 80
2.50E-03
2.00E-03
1.50E-03
1.00E-03
5.00E-04
0.00E+00
H/I
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-86

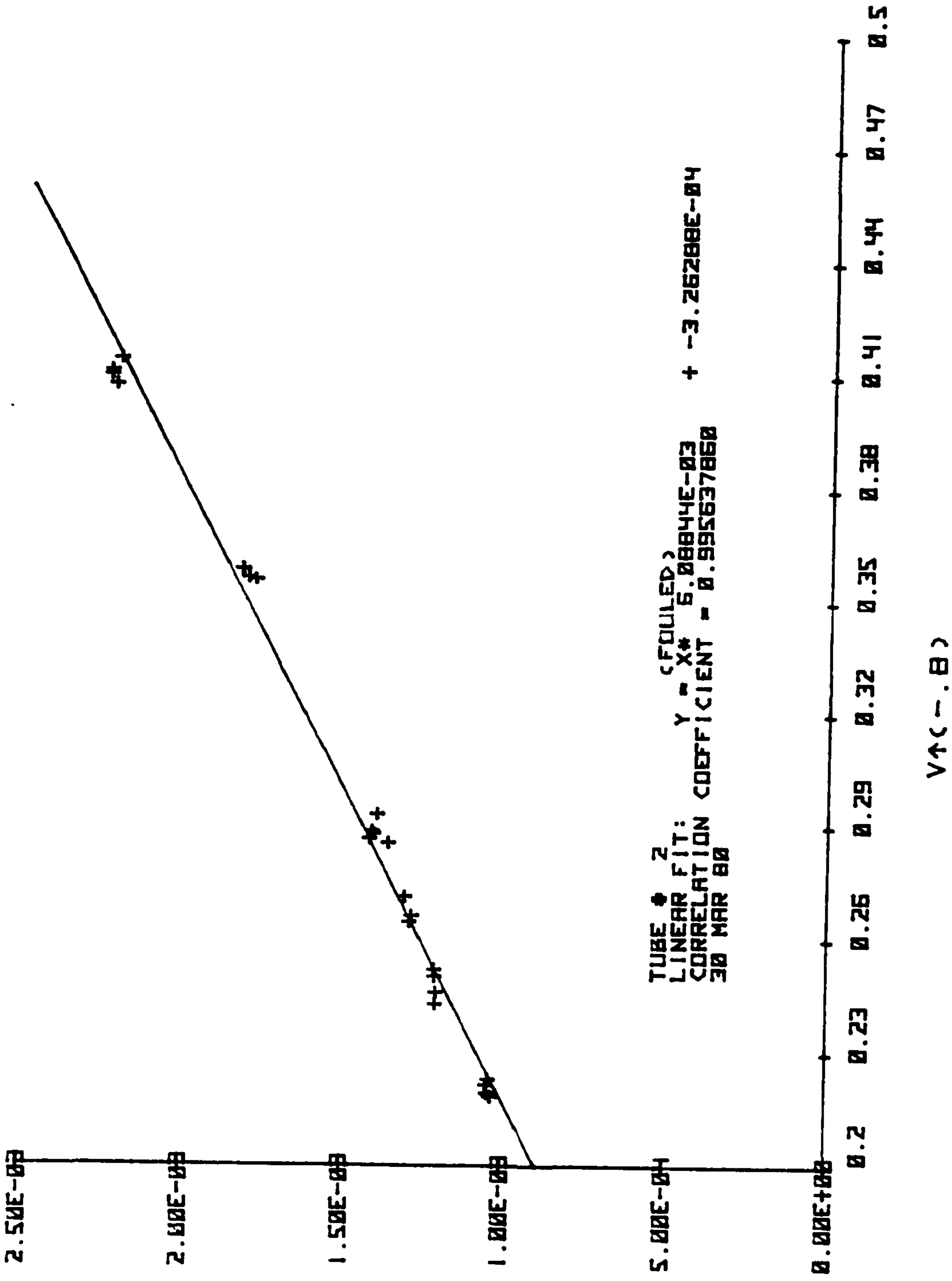

TUBE # 2 (FOULED)
LINEAR FIT: Y = X* 6.08844E-03 + -3.26208E-04
CORRELATION COEFFICIENT = 0.995637860
30 MAR 80
H/I
2.50E-03
2.00E-03
1.50E-03
1.00E-03
5.00E-04
0.00E+00
V↑(-.8)
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-87

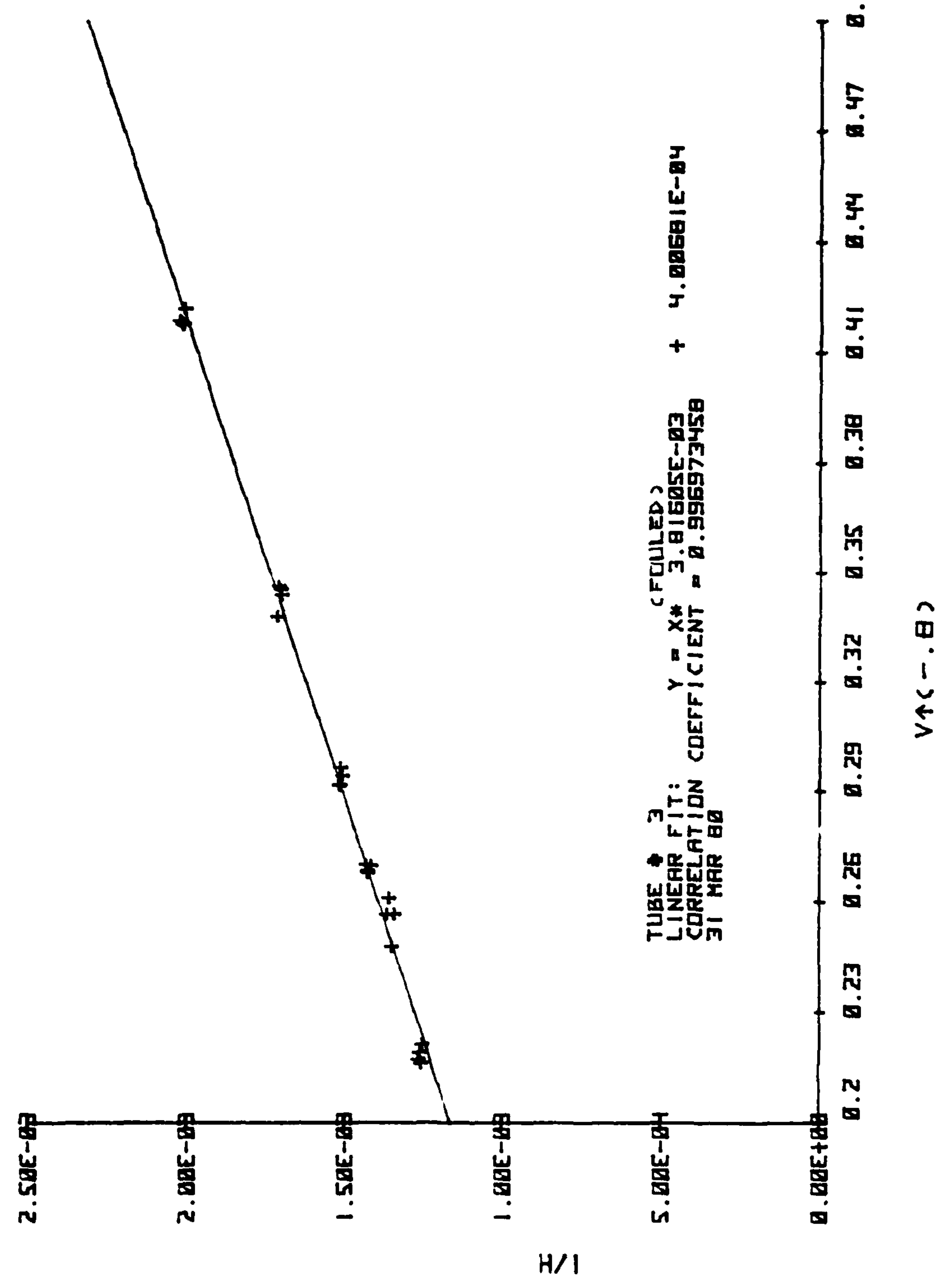

TUBE # 3
LINEAR FIT: Y = X* 3.81605E-03 + 4.00681E-04
(FOULED)
CORRELATION COEFFICIENT = 0.996973458
31 MAR 80
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)
0.00E+00
5.00E-04
1.00E-03
1.50E-03
2.00E-03
2.50E-03
H/I

FIGURE B-88

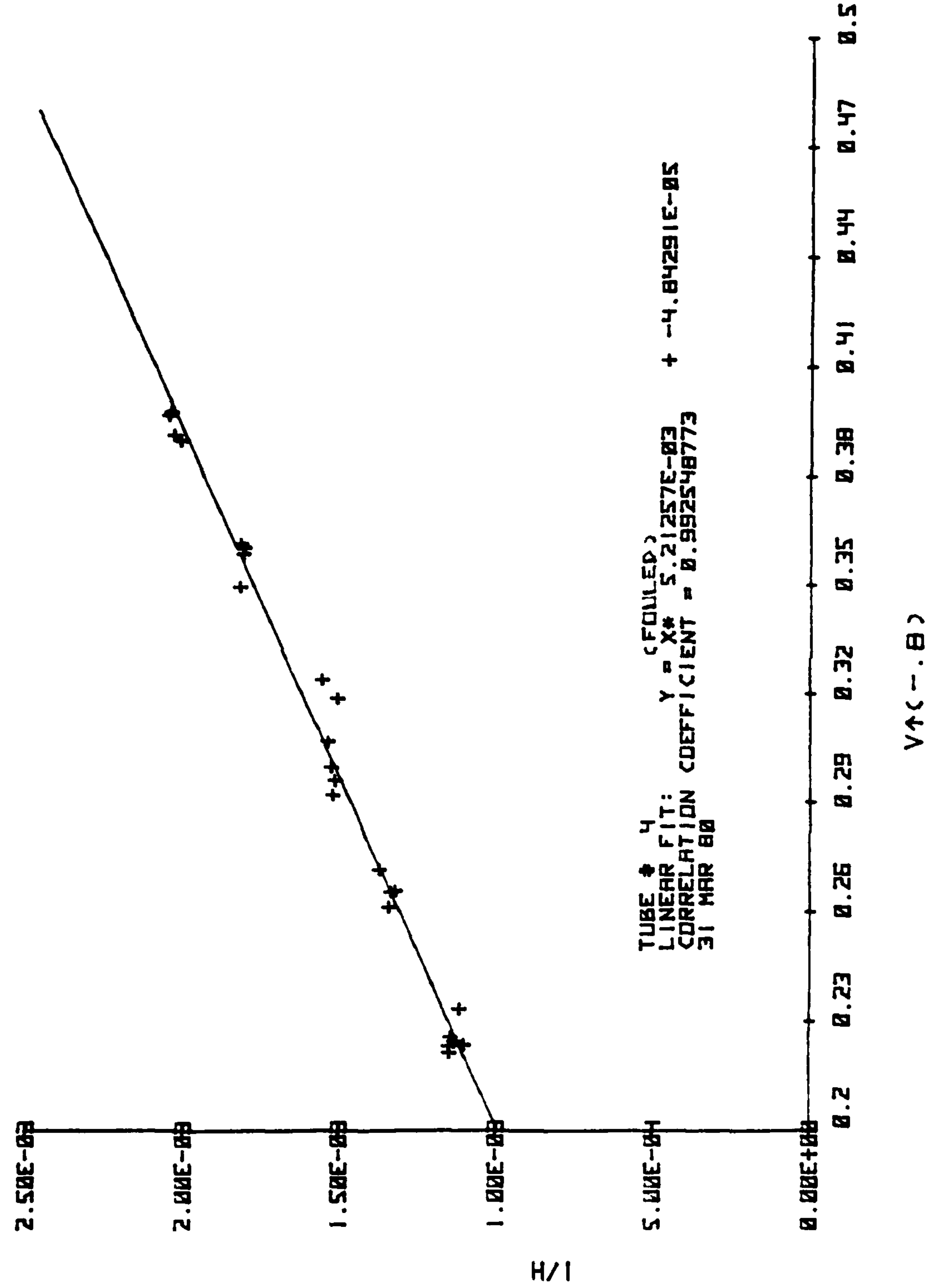

TUBE # 4
(FOULED)
LINEAR FIT: Y = X* 5.212257E-03 + -4.84291E-05
CORRELATION COEFFICIENT = 0.992548773
31 MAR 80
H/I
2.50E-03
2.00E-03
1.50E-03
1.00E-03
5.00E-04
0.00E+00
V↑(-.8)
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-89

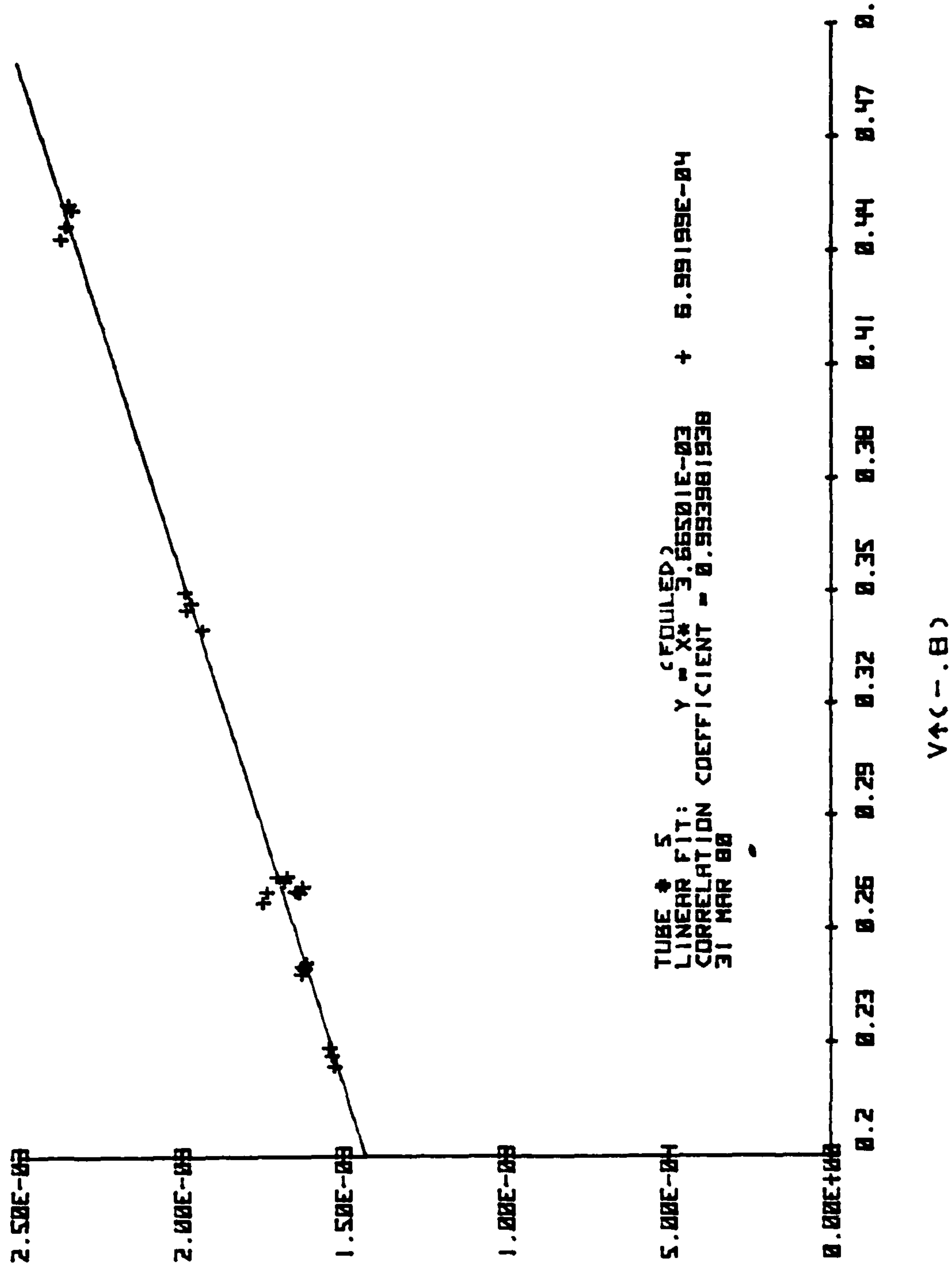

TUBE # 5 (FOULED)
LINEAR FIT: Y = X* 3.66501E-03 + 6.99199E-04
CORRELATION COEFFICIENT = 0.993981938
31 MAR 80
H/I
V↑(-.8)
2.50E-03
2.00E-03
1.50E-03
1.00E-03
5.00E-04
0.00E+00
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-90

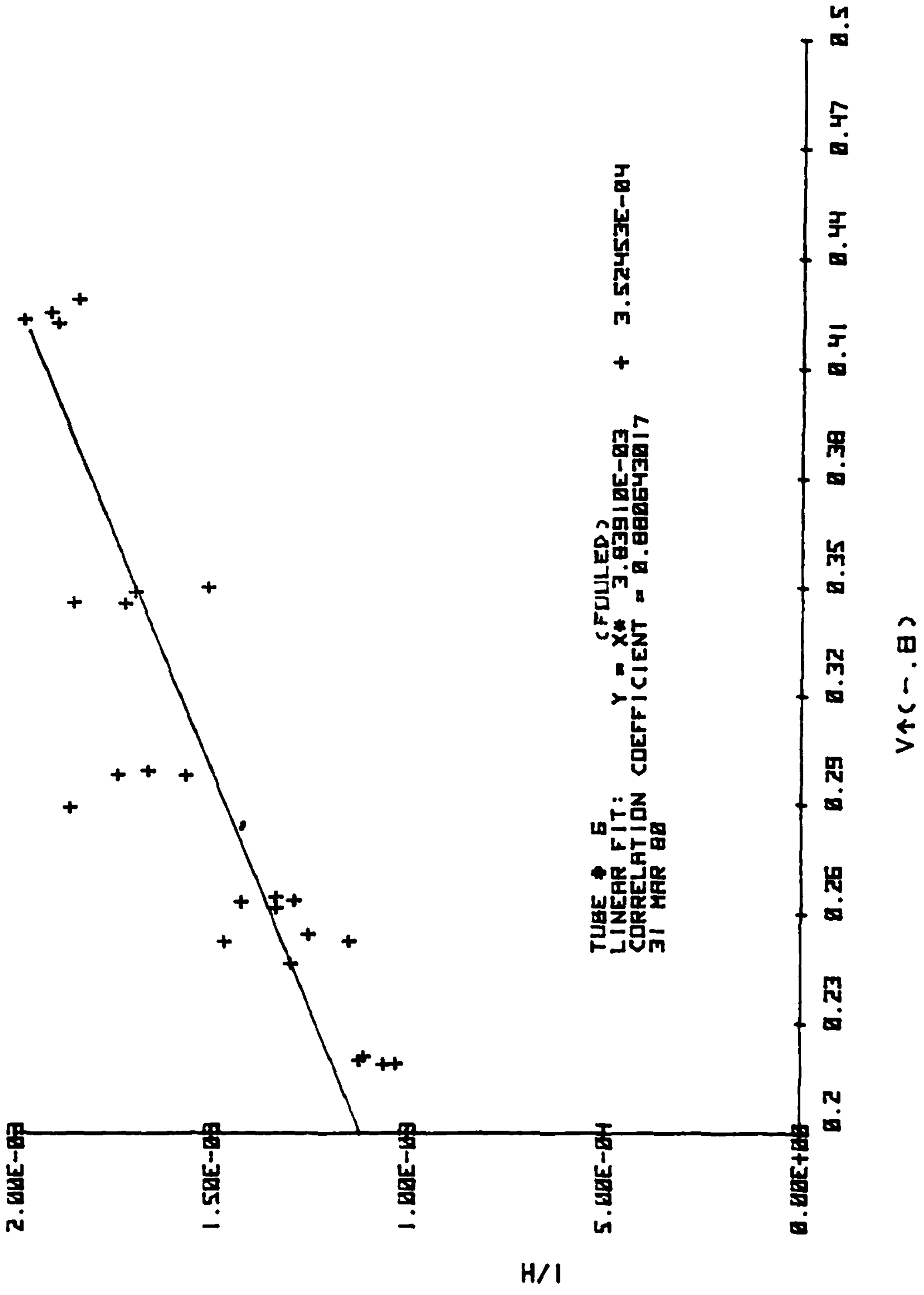

TUBE # 6 (FOULED)
LINEAR FIT: Y = X* 3.83910E-03 + 3.52453E-04
CORRELATION COEFFICIENT = 0.880643017
31 MAR 80
2.00E-03
1.50E-03
1.00E-03
5.00E-04
0.00E+00
H/I
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-91

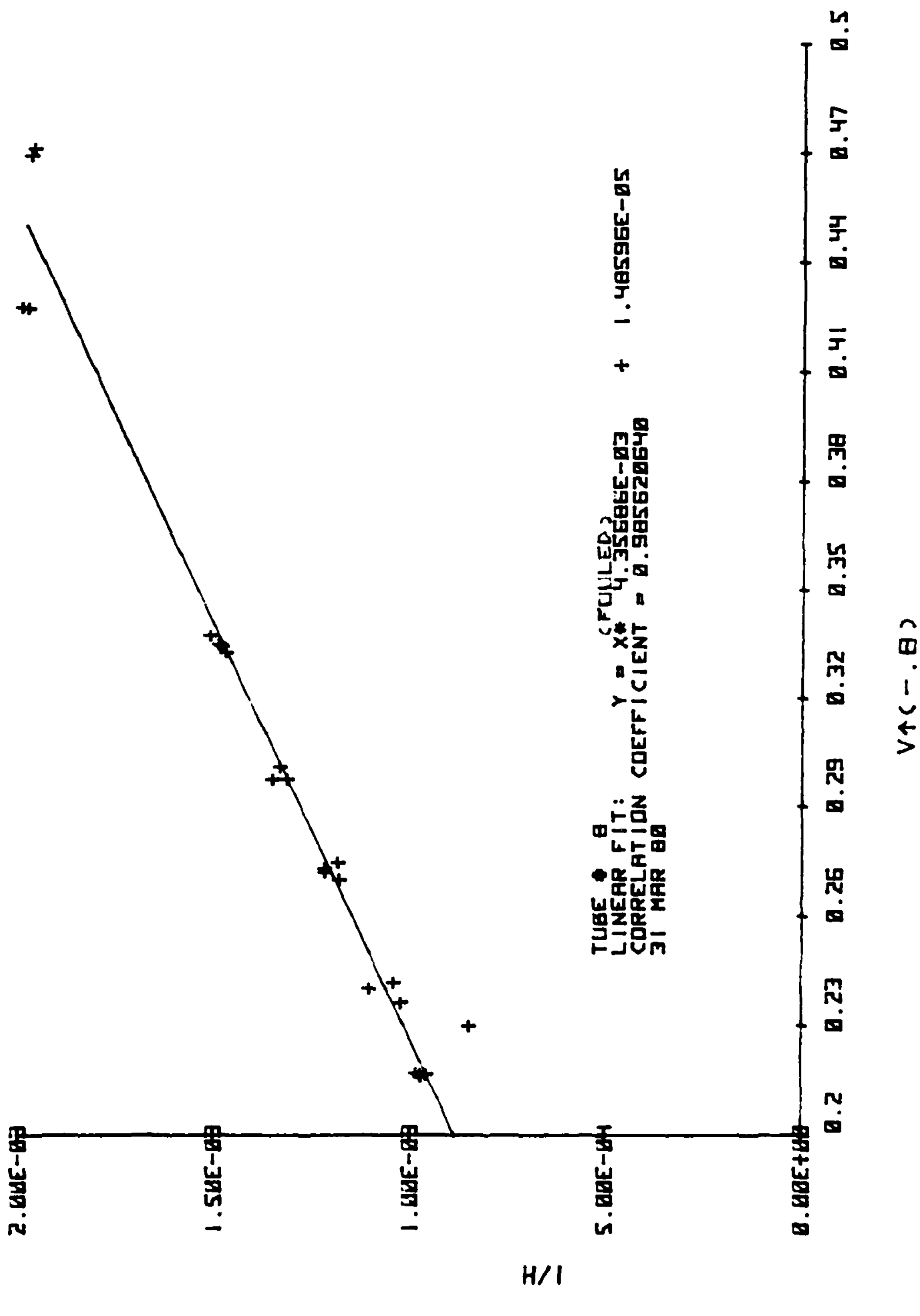

TUBE # 8
(FOULED)
LINEAR FIT: Y = X* 4.35686E-03 + 1.48596E-05
CORRELATION COEFFICIENT = 0.985620640
31 MAR 80
H/I
2.00E-03
1.50E-03
1.00E-03
5.00E-04
0.00E+00
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-92

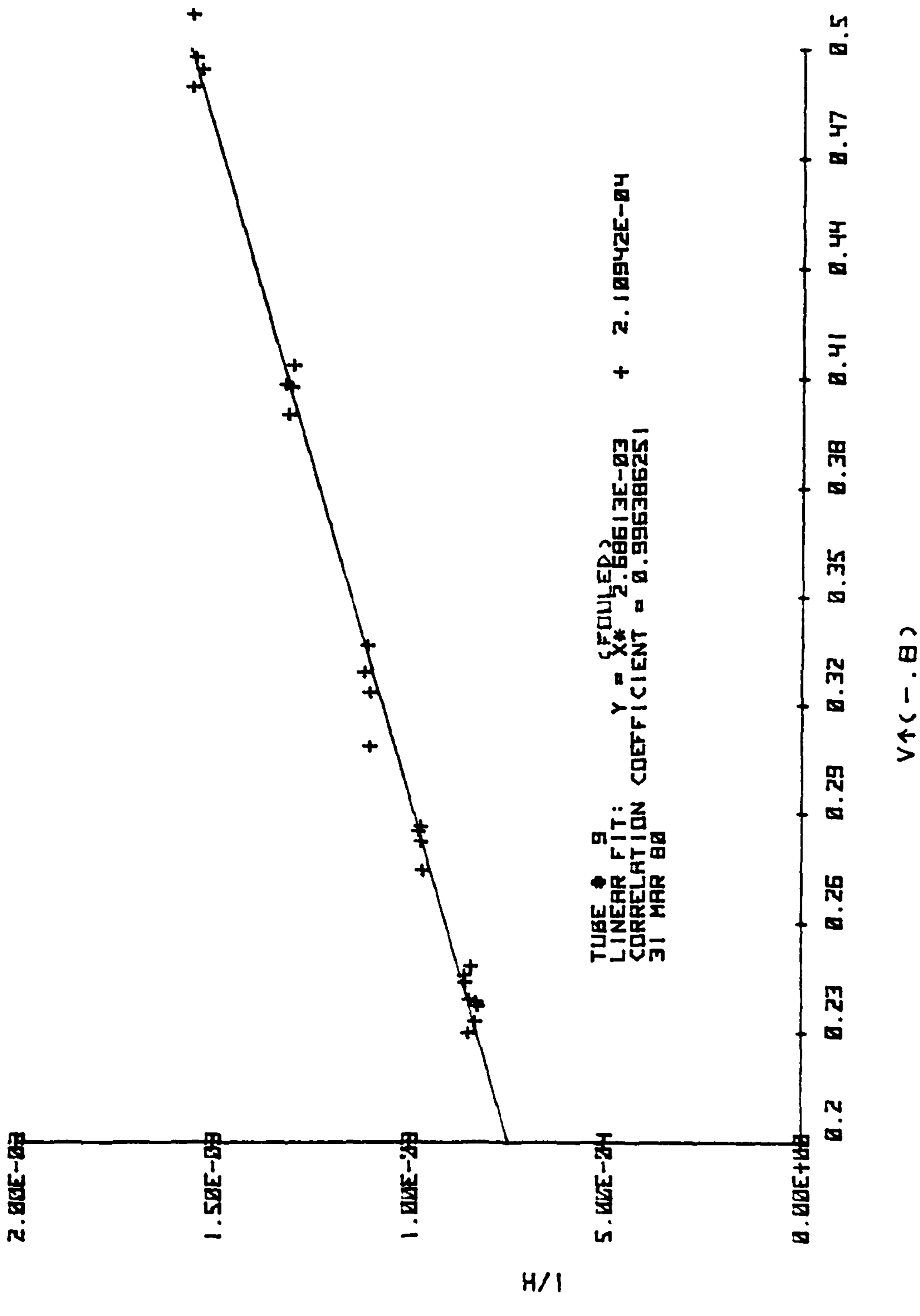

TUBE # 9
LINEAR FIT: Y = (FOULED) X* 2.68613E-03 + 2.10942E-04
CORRELATION COEFFICIENT = 0.996386251
31 MAR 80
1/H
V↑(-.8)
0.00E+00
5.00E-04
1.00E-03
1.50E-03
2.00E-03
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5

FIGURE B-93

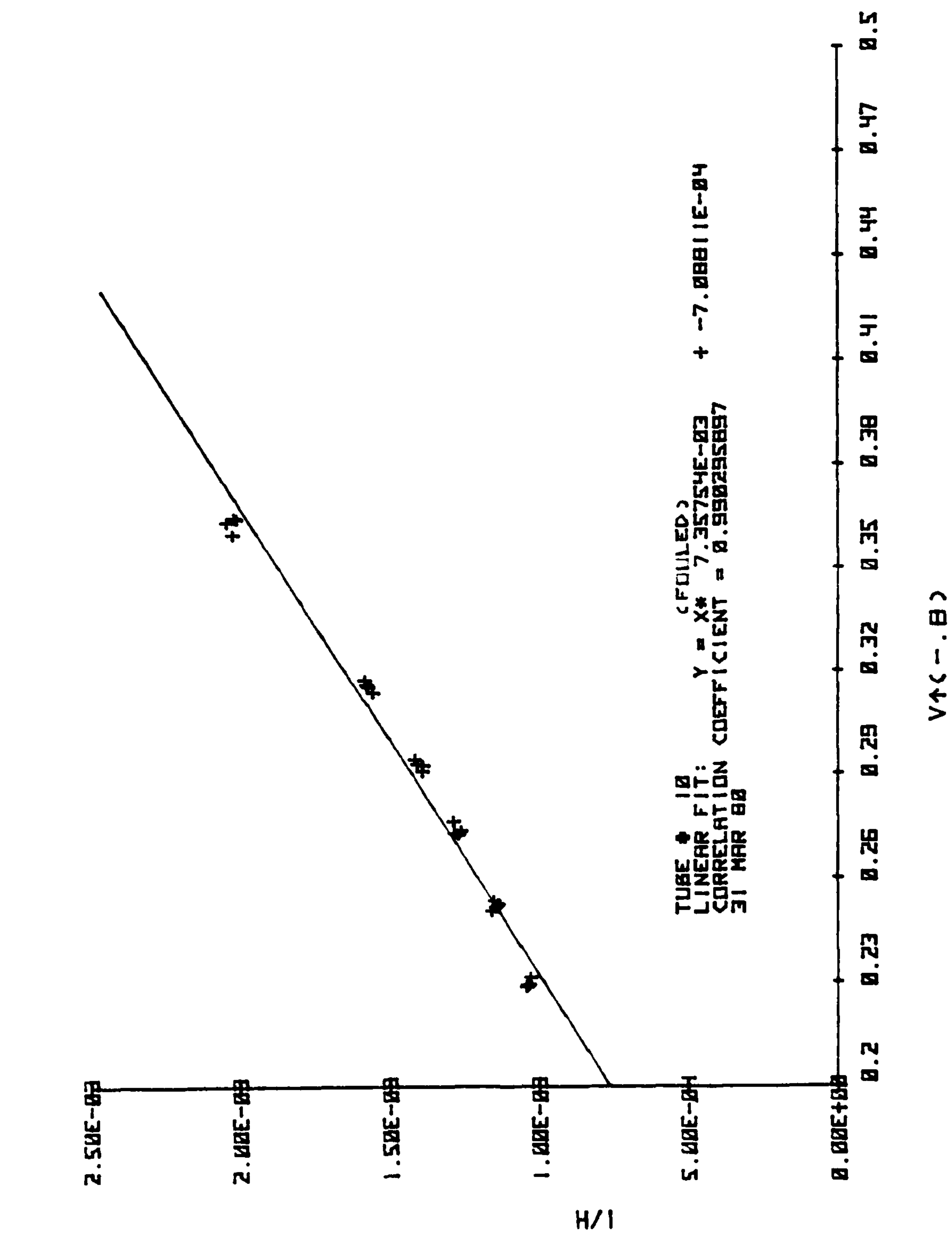

TUBE # 10 (FOULED)
LINEAR FIT: Y = X* 7.35754E-03 + -7.08811E-04
CORRELATION COEFFICIENT = 0.990295897
31 MAR 80
2.50E-03
2.00E-03
1.50E-03
1.00E-03
5.00E-04
0.00E+00
H/I
0.2
0.23
0.26
0.29
0.32
0.35
0.38
0.41
0.44
0.47
0.5
V↑(-.8)

FIGURE B-94

APPENDIX C

MONTHLY PLOTS OF Rf IN ALUMINUM PIPE

USING FLOW-DRIVEN BRUSHES

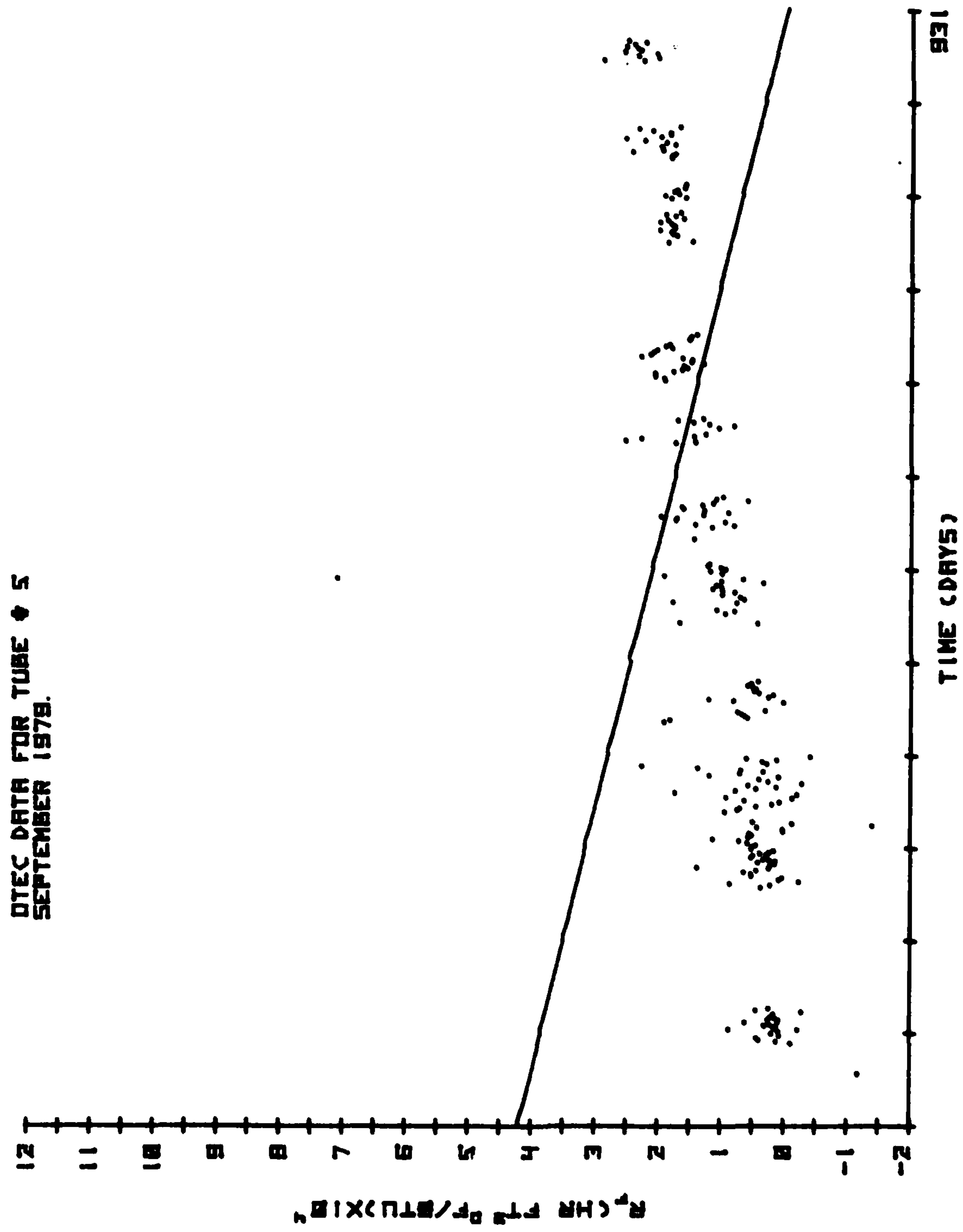

OTEC DATA FOR TUBE # 5
SEPTEMBER 1979.
TIME (DAYS)
128
R_f (HR FT² °F/BTU)X10⁴
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE C-1.

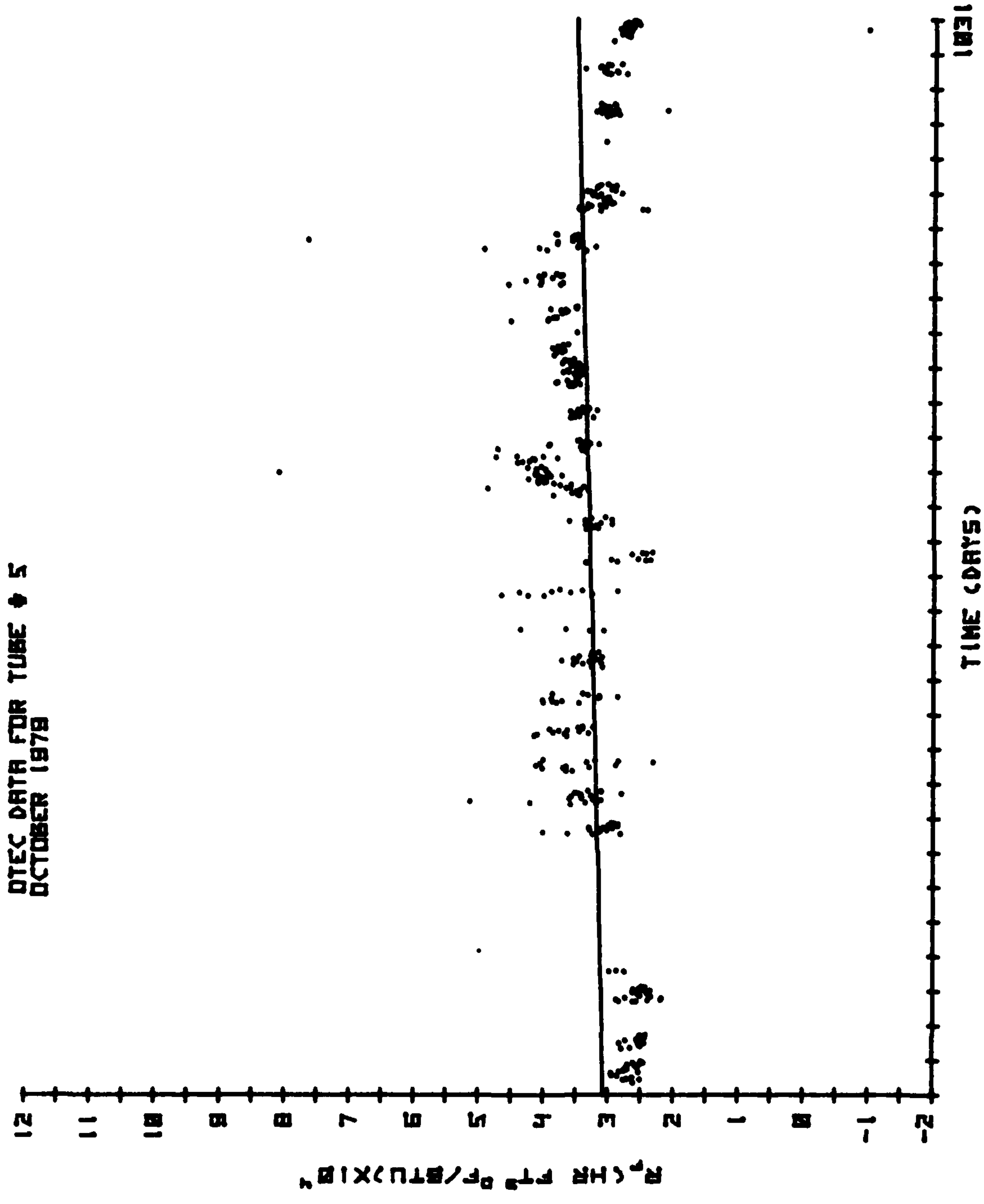

OTEC DATA FOR TUBE # 5
OCTOBER 1979
TIME (DAYS)
R (HR FT °F/BTU)X10
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE C-2.

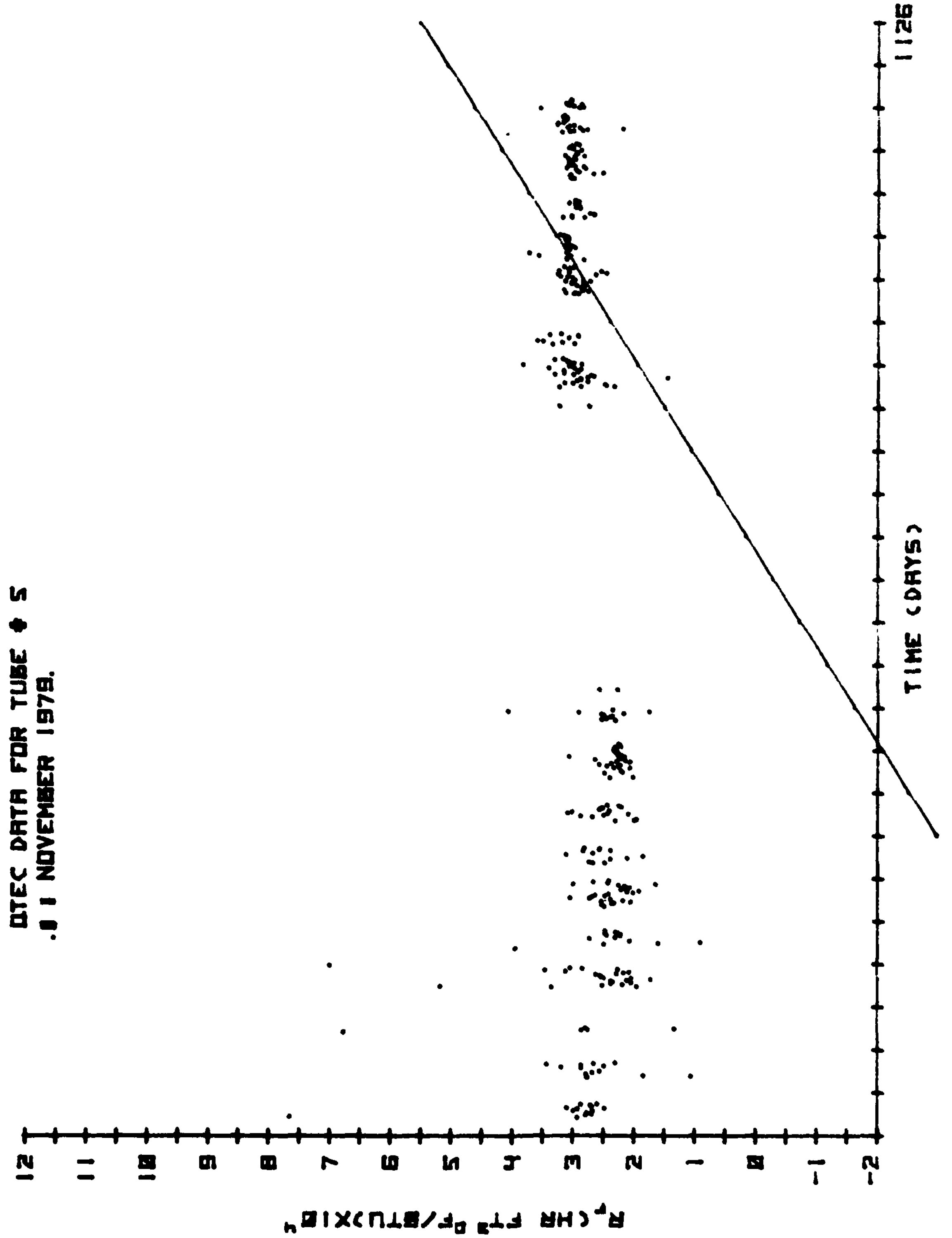

DTEC DATA FOR TUBE # 5
1 NOVEMBER 1979.
TIME (DAYS)
1126
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
Rf (HR FT2 °F/BTU)X10

FIGURE C-3.

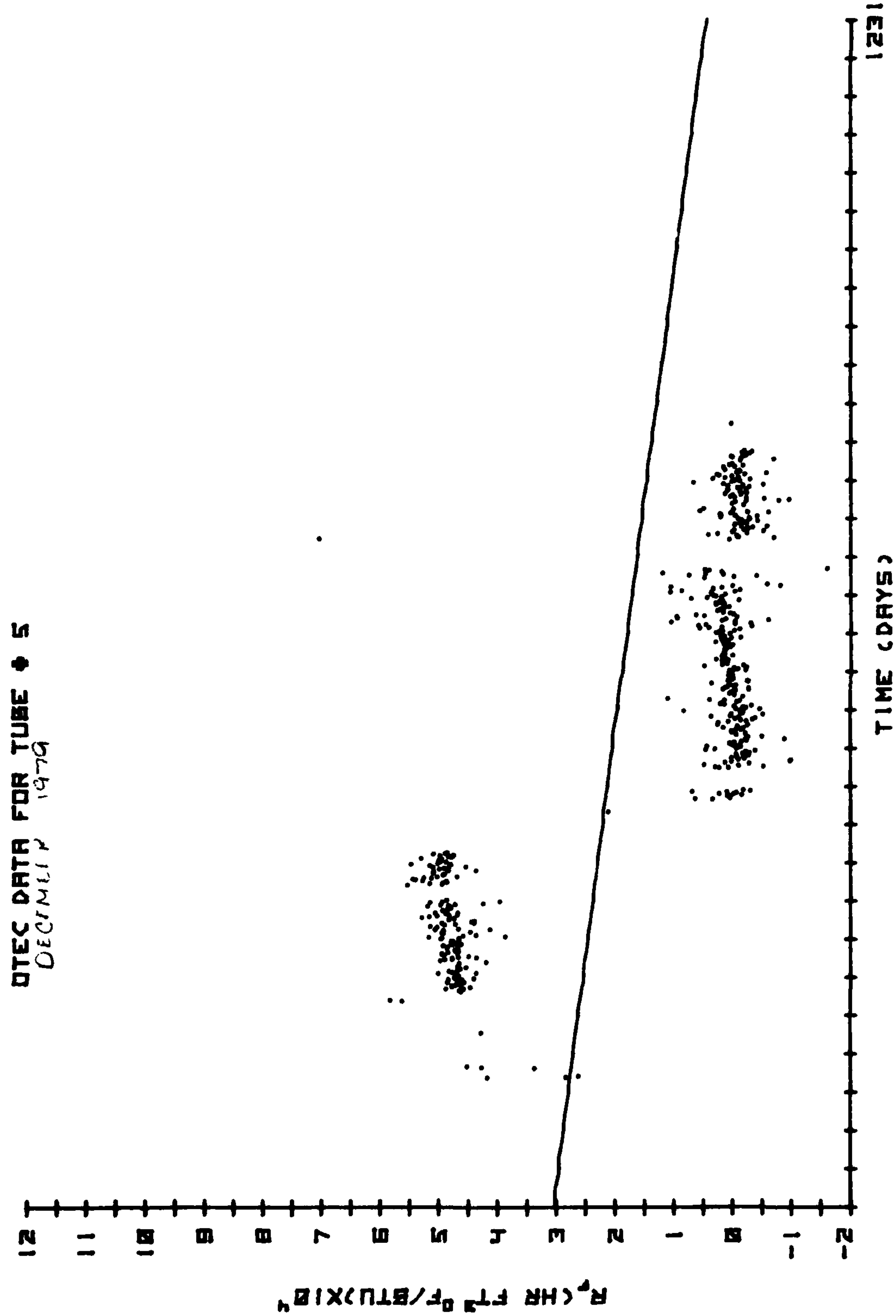

OTEC DATA FOR TUBE # 5
DECEMBER 1979
TIME (DAYS)
123
R_f (HR FT^2 °F/BTU)X10^4
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE C-4.

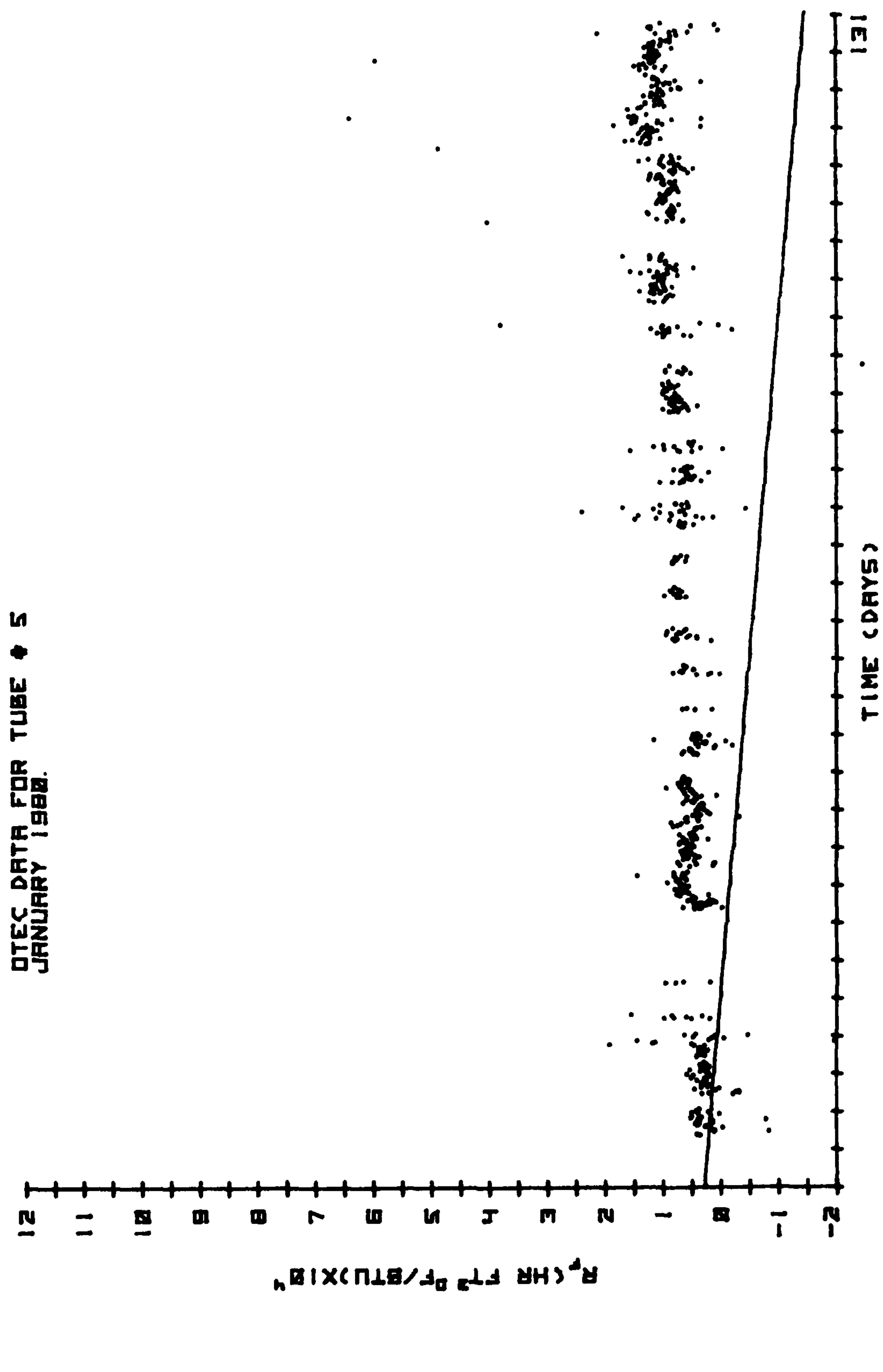

OTEC DATA FOR TUBE # 5
JANUARY 1980
TIME (DAYS)
131
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
R_f (HR FT^2 °F/BTU)X10^4

FIGURE C-5.

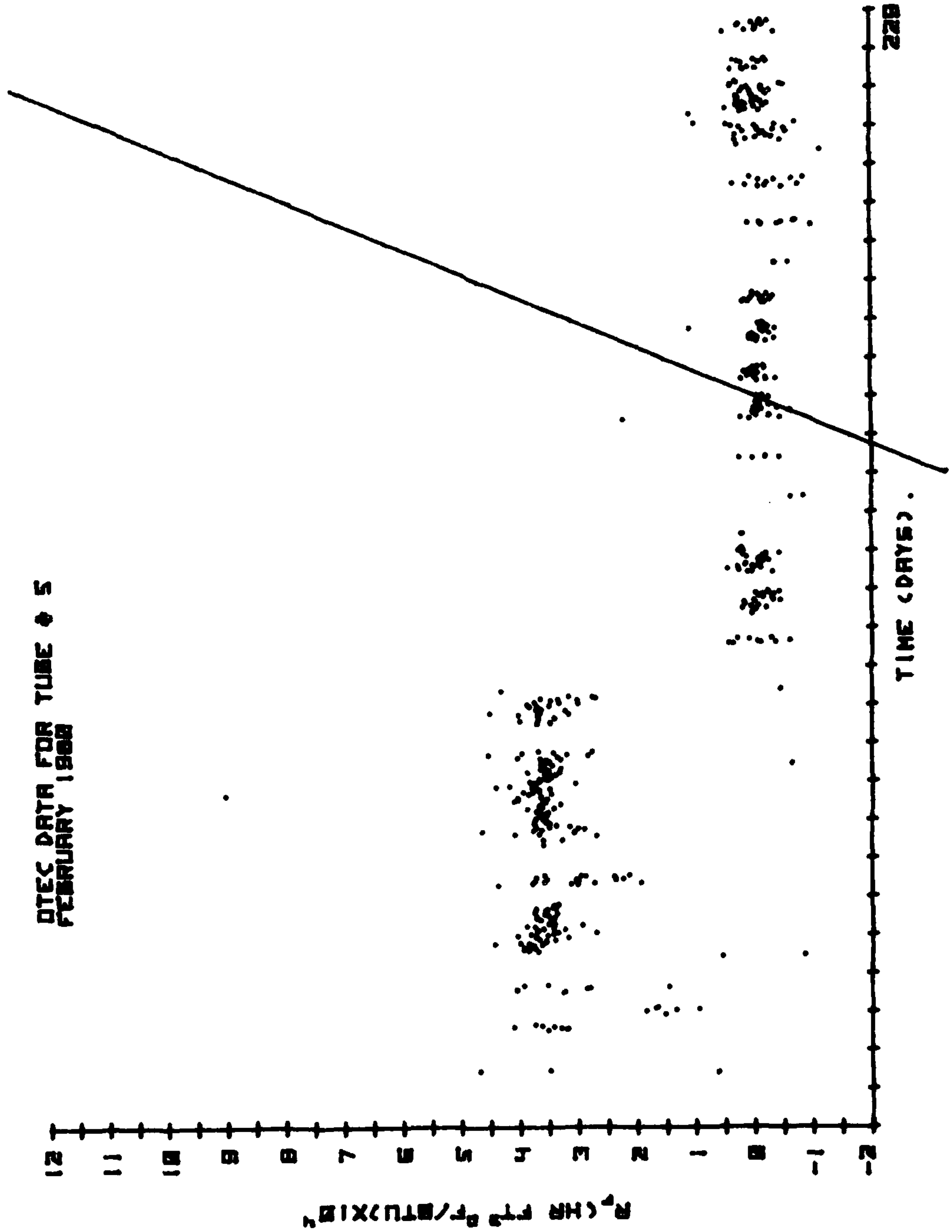

OTEC DATA FOR TUBE # 5
FEBRUARY 1980
TIME (DAYS)
229
R$_f$ (HR FT^2 °F/BTU)X10^4
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE C-6.

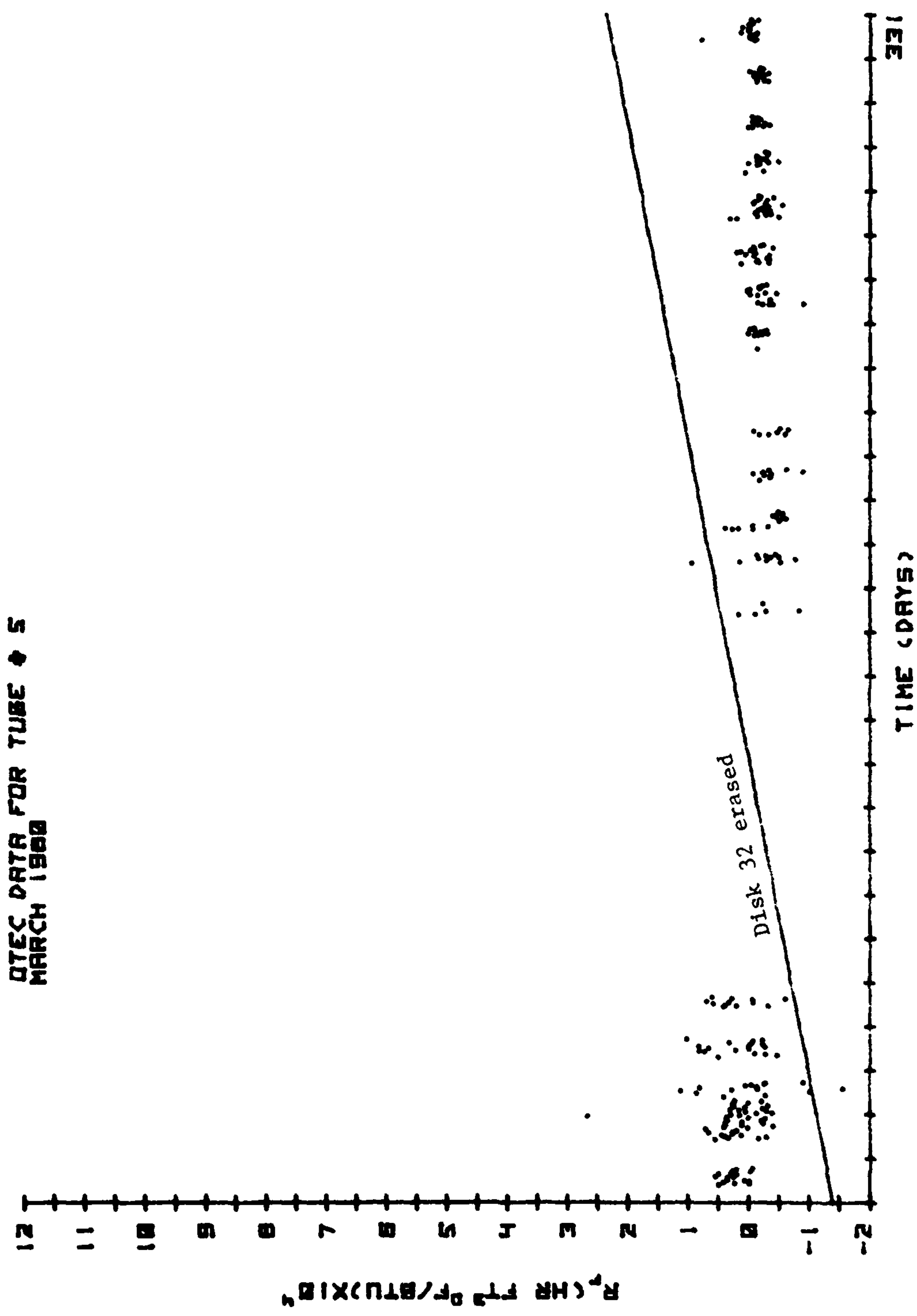

OTEC DATA FOR TUBE # 5
MARCH 1980
Disk 32 erased
TIME (DAYS)
331
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
R_f (HR FT² °F/BTU)X10⁴

FIGURE C-7.

APPENDIX D

MONTHLY PLOTS OF Rf IN TITANIUM PIPE USING FLOW-DIRVEN BRUSHES

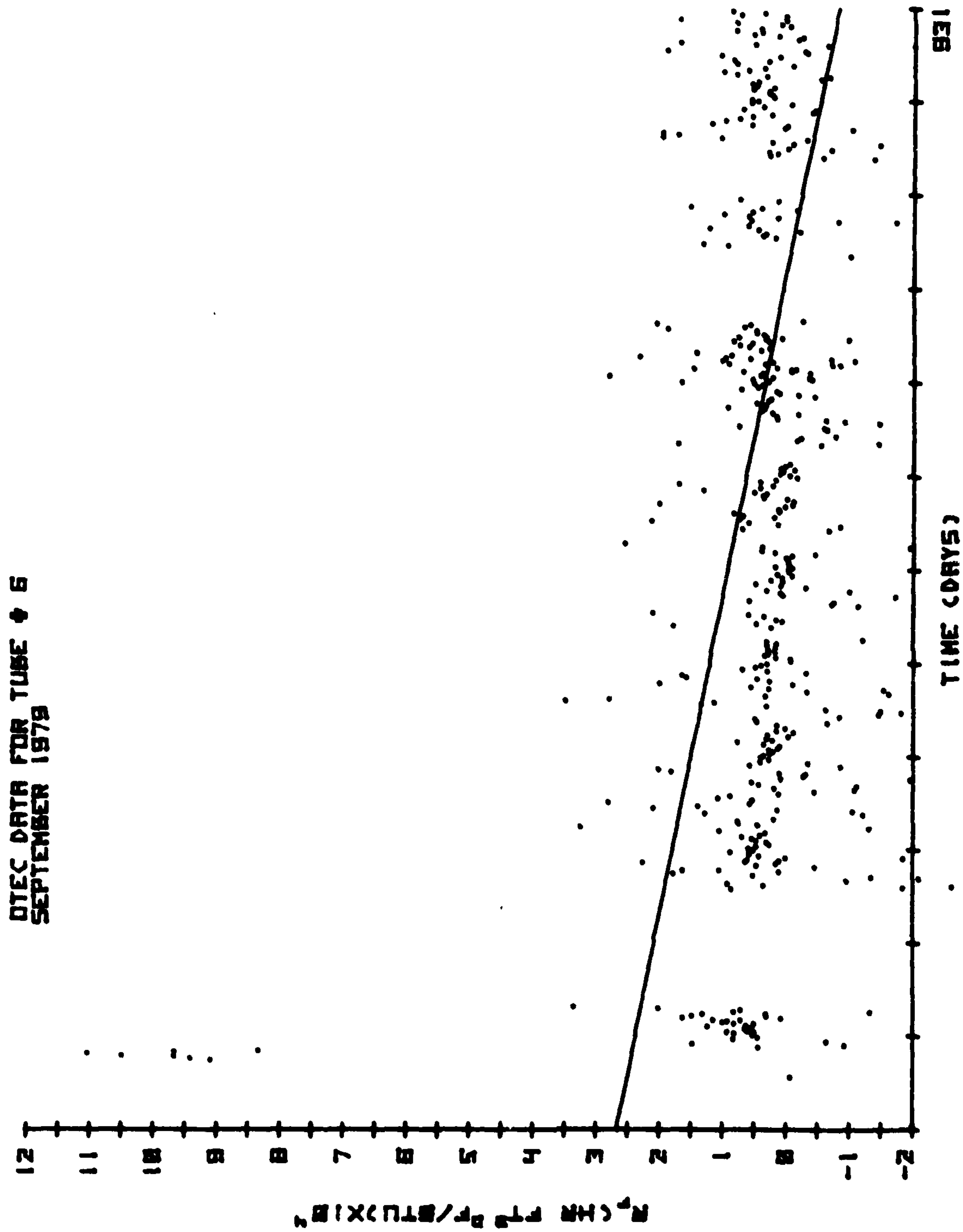

DTEC DATA FOR TUBE # 6
SEPTEMBER 1979
TIME (DAYS)
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE D-1.

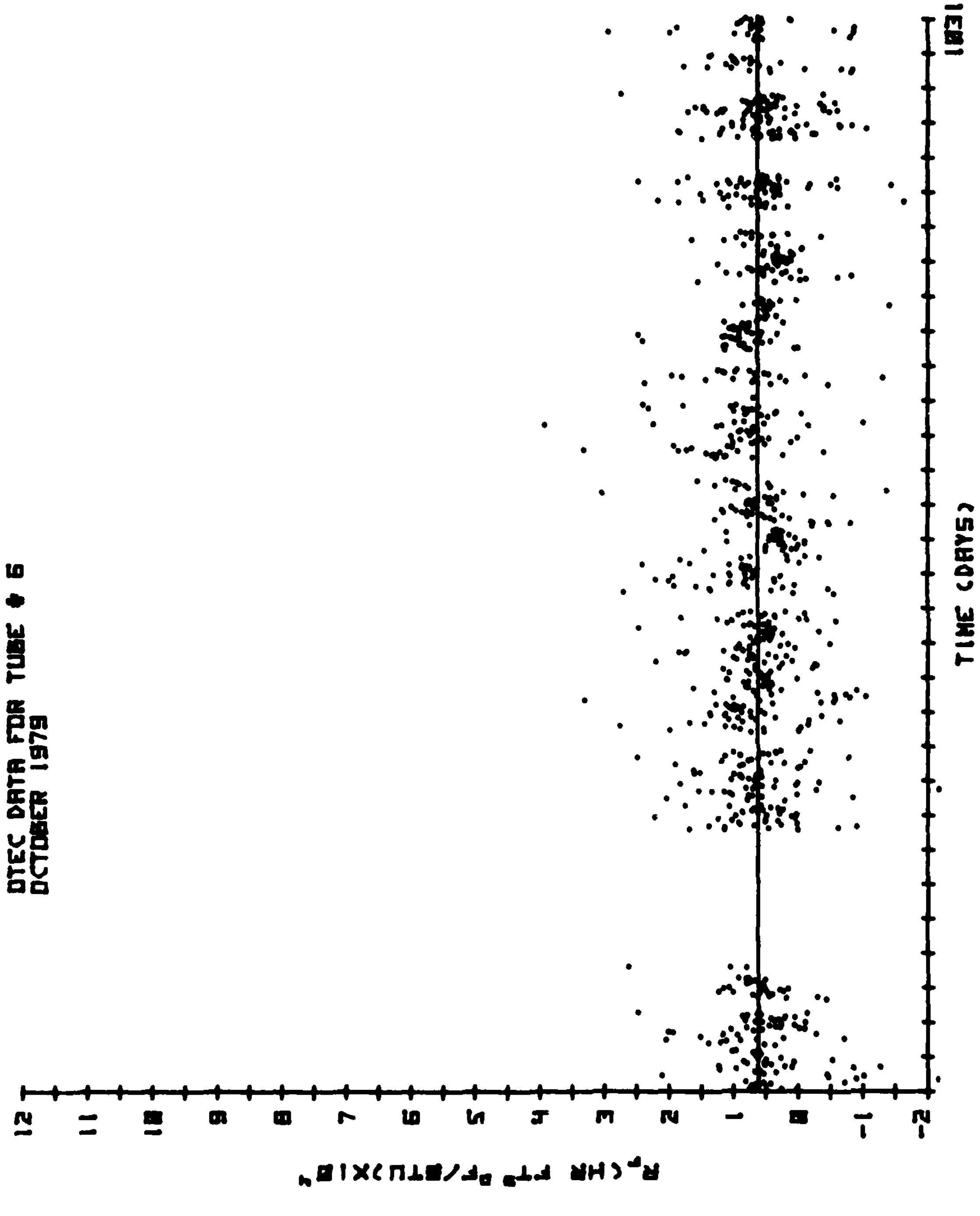

DTEC DATA FOR TUBE # 6
OCTOBER 1979
TIME (DAYS)
R_f (HR FT² °F/BTU)X10⁴
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE D-2.

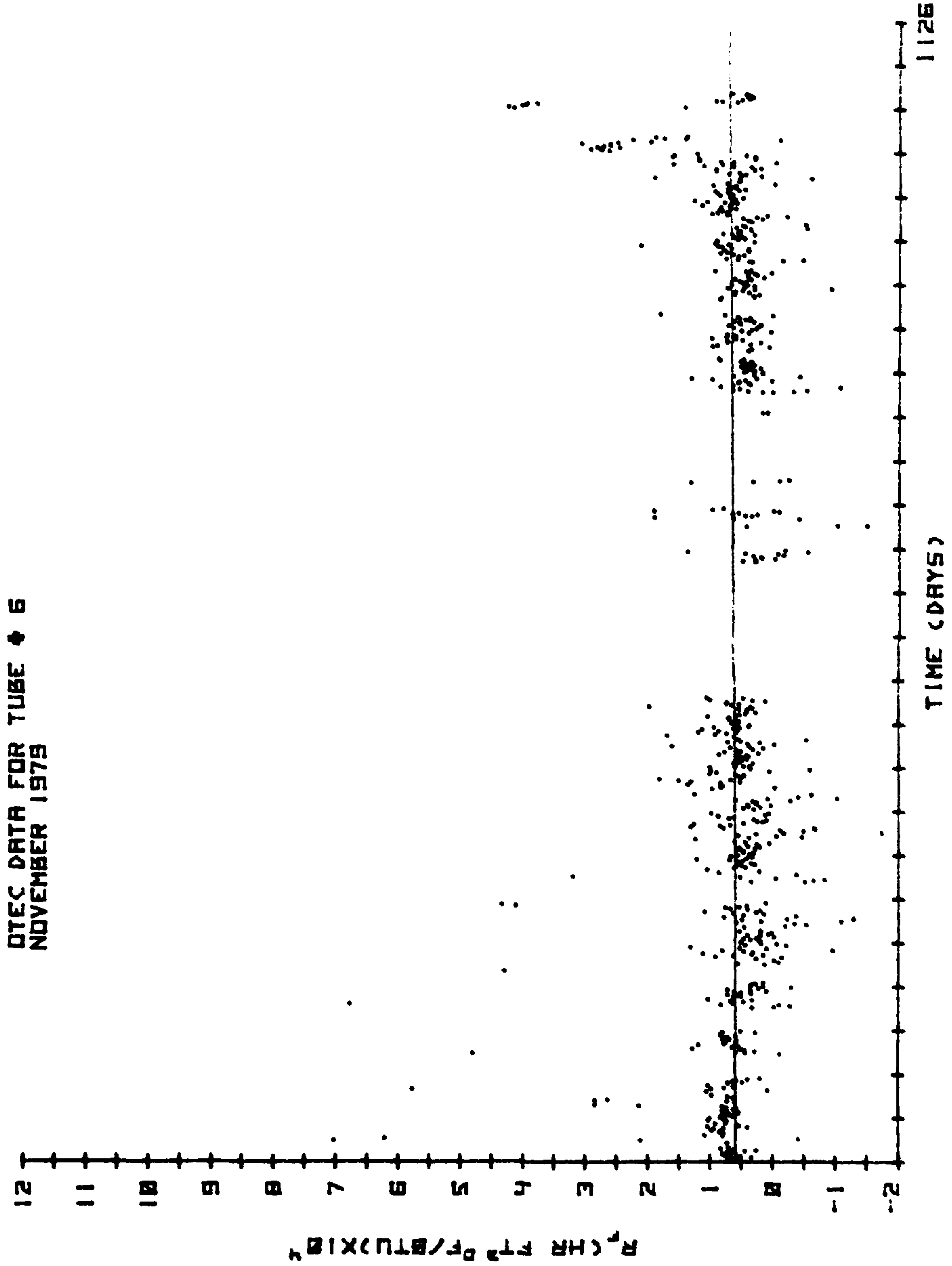

OTEC DATA FOR TUBE # 6
NOVEMBER 1979
TIME (DAYS)
1126
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
Rf (HR FT2 °F/BTU) X10^4

FIGURE D-3.

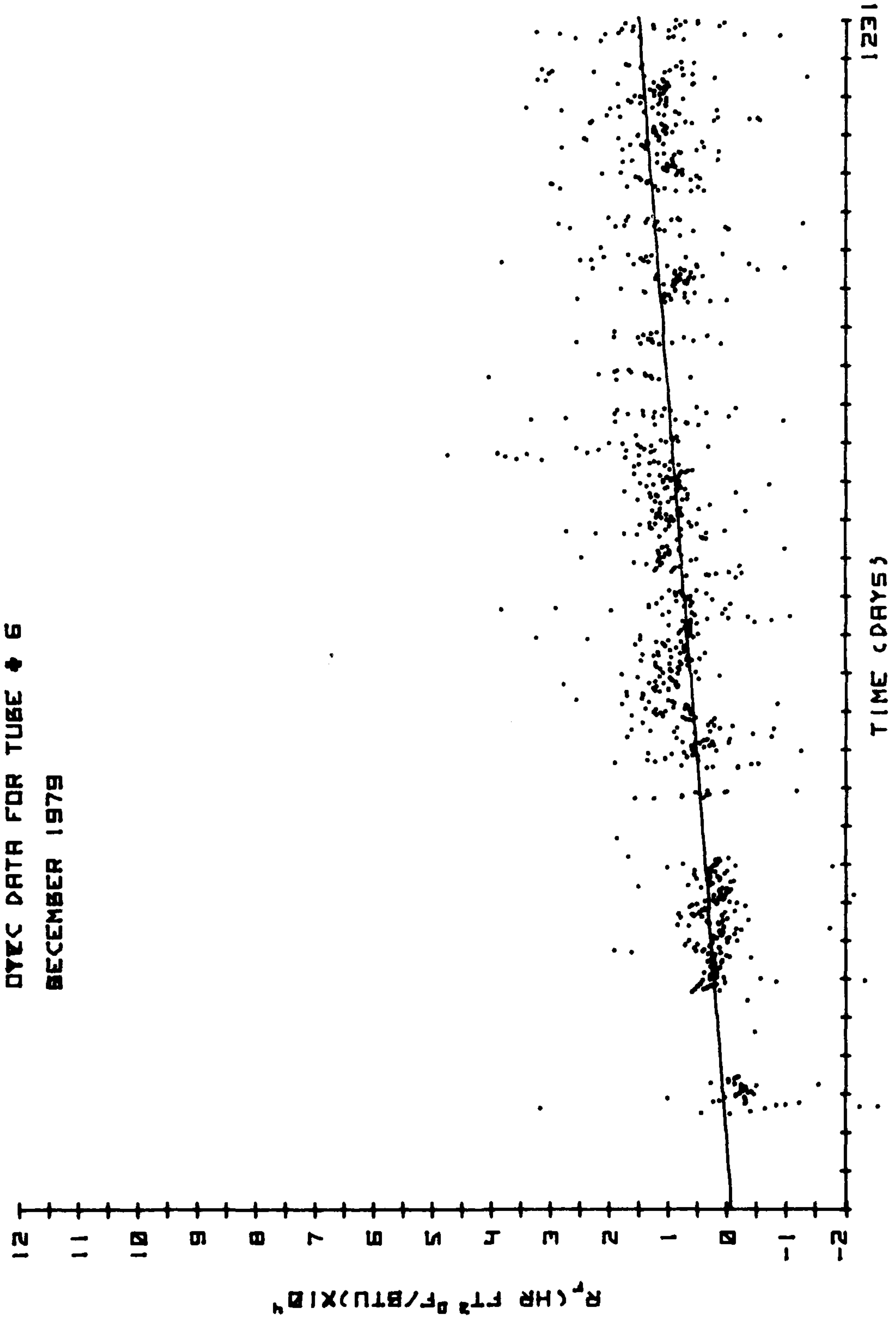

OTEC DATA FOR TUBE # 6
DECEMBER 1979
TIME (DAYS)
1231
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
Rf (HR FT2 oF/BTU)X10^4

FIGURE D-4.

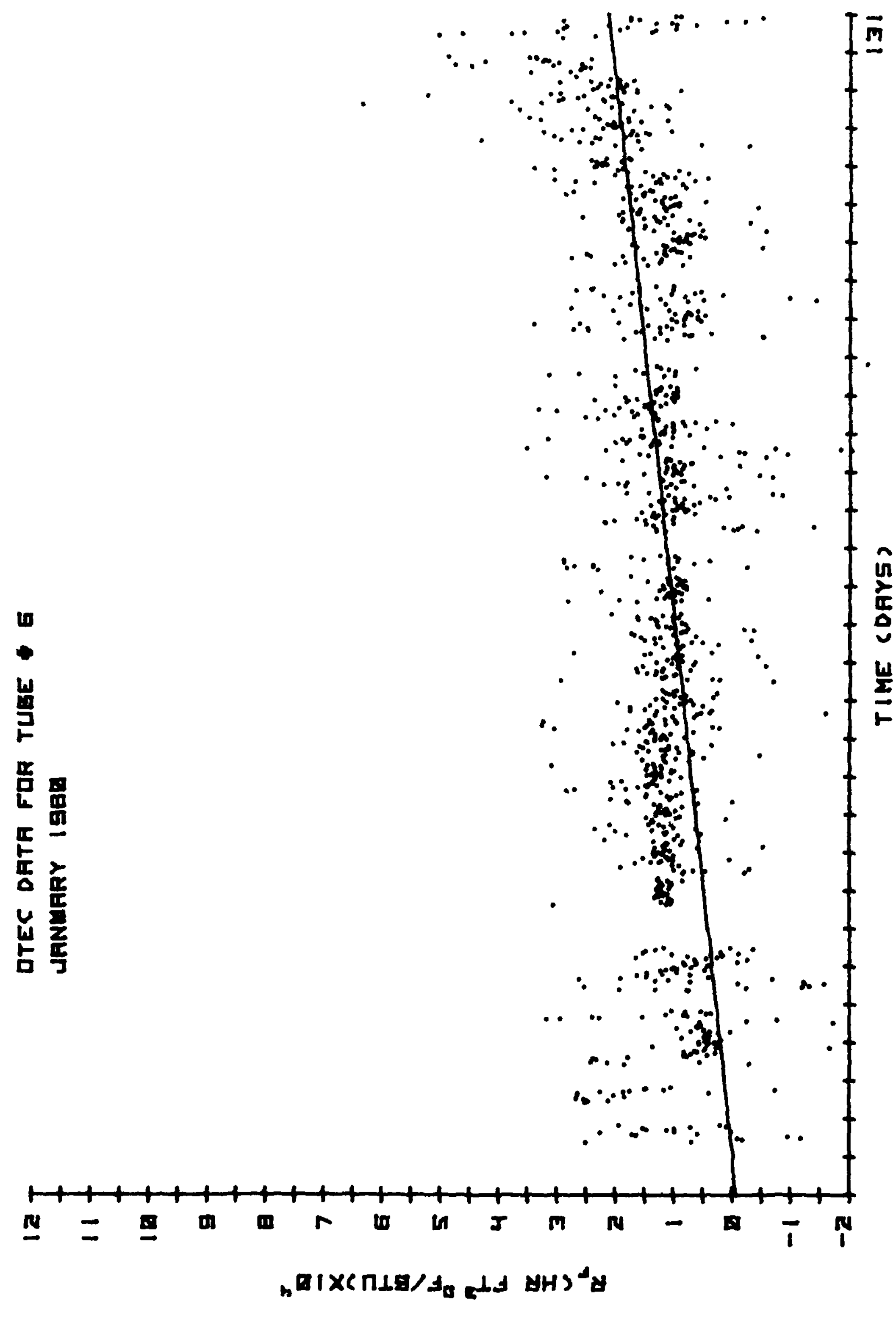

OTEC DATA FOR TUBE # 6
JANUARY 1980
TIME (DAYS)
31
R_f (HR FT² °F/BTU) X10⁴
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE D-5.

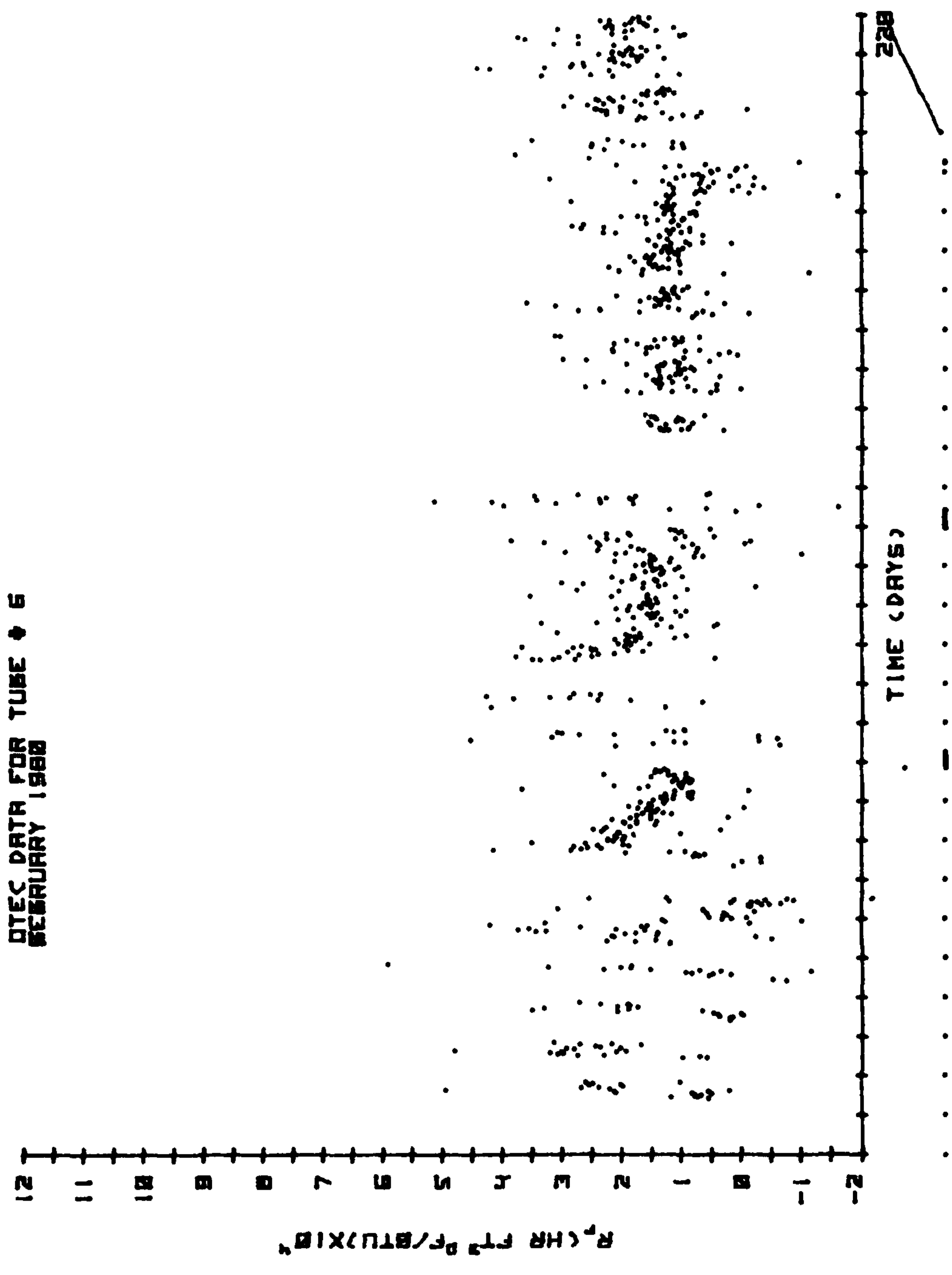
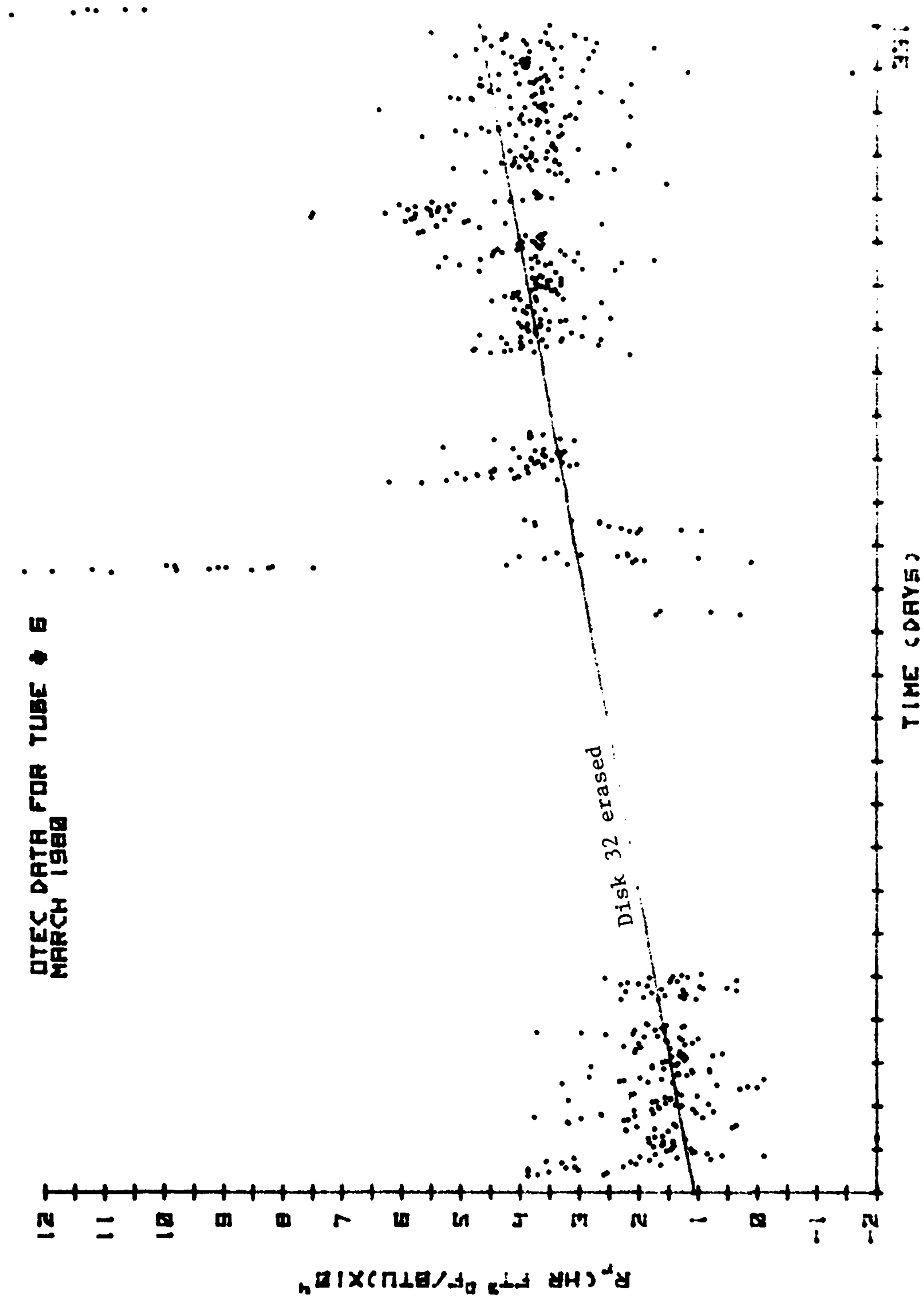

OTEC DATA FOR TUBE # 6
FEBRUARY 1980
TIME (DAYS)
230
R_f (HR FT² °F/BTU)X10⁴
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE D-6.



OTEC DATA FOR TUBE # 6
MARCH 1980
Disk 32 erased
TIME (DAYS)
R_f (HR FT² °F/BTU)X10⁴
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE D-7.

APPENDIX E

MONTHLY PLOTS OF Rf IN ALUMINUM PIPE USING RECIRCULATING SPONGE RUBBER BALLS

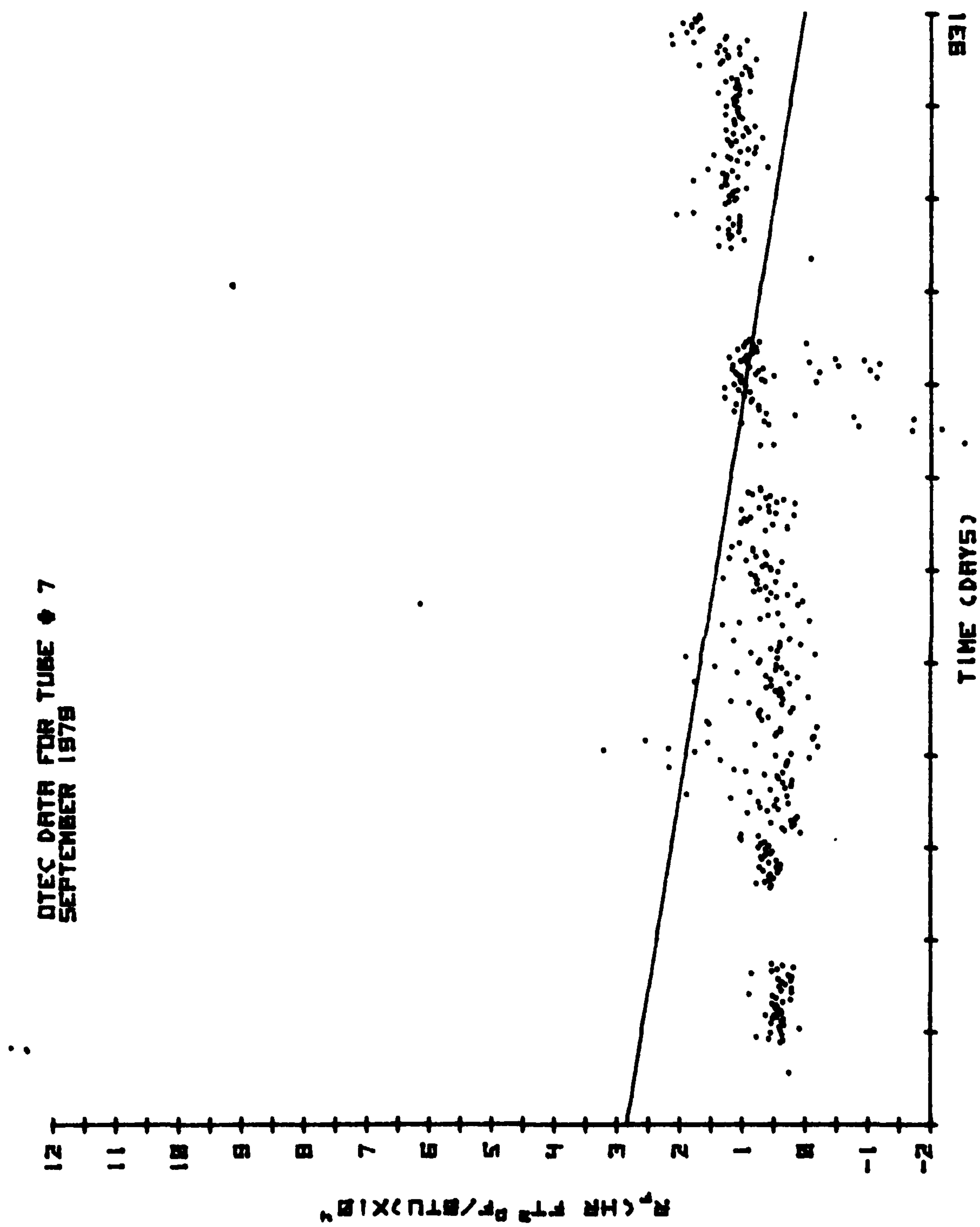

OTEC DATA FOR TUBE # 7
SEPTEMBER 1979
TIME (DAYS)
168
R_f (HR FT² °F/BTU)X10⁴
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE E-1.

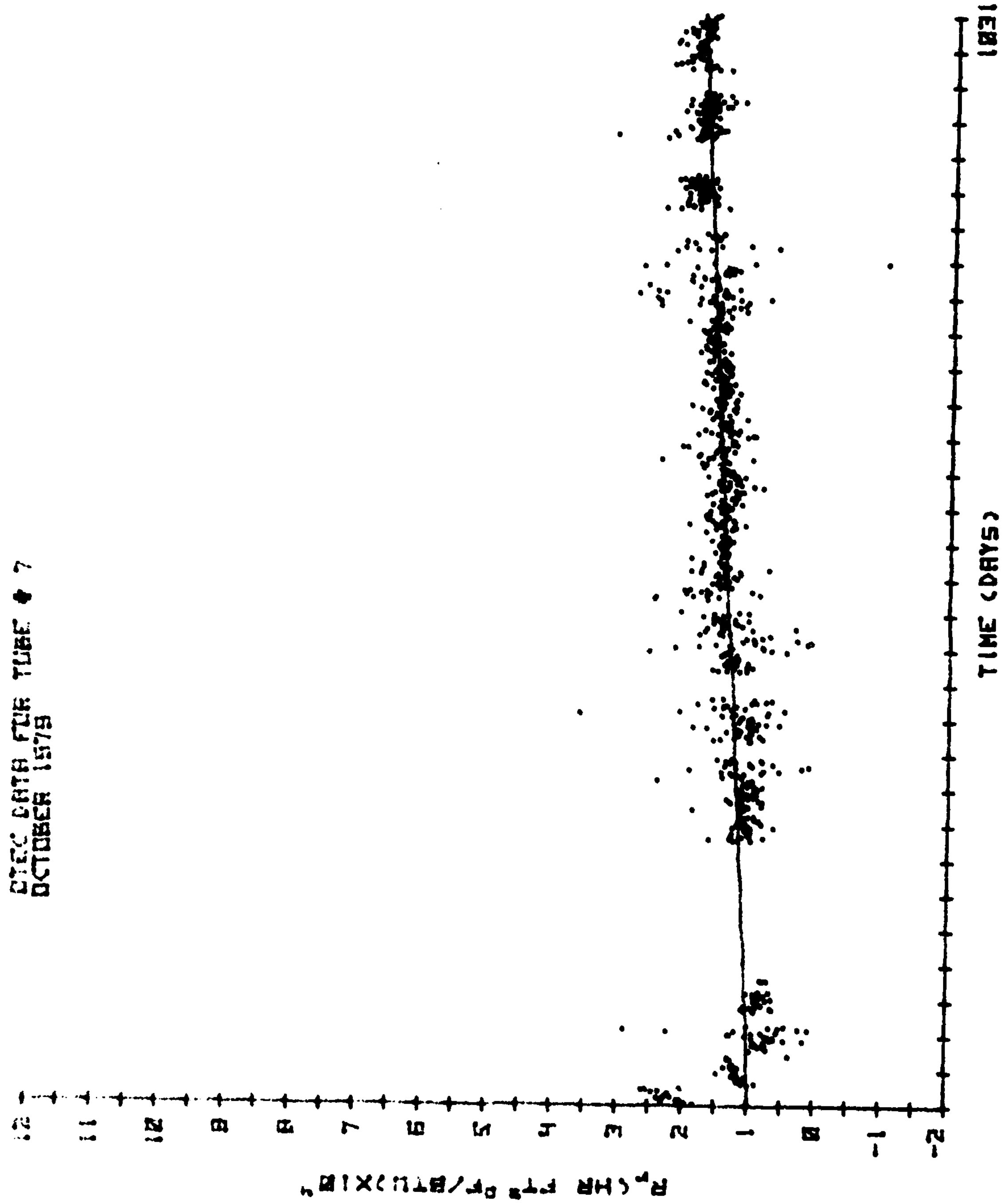

DTRC DATA FOR TUBE # 7
OCTOBER 1979
TIME (DAYS)
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE E-2.

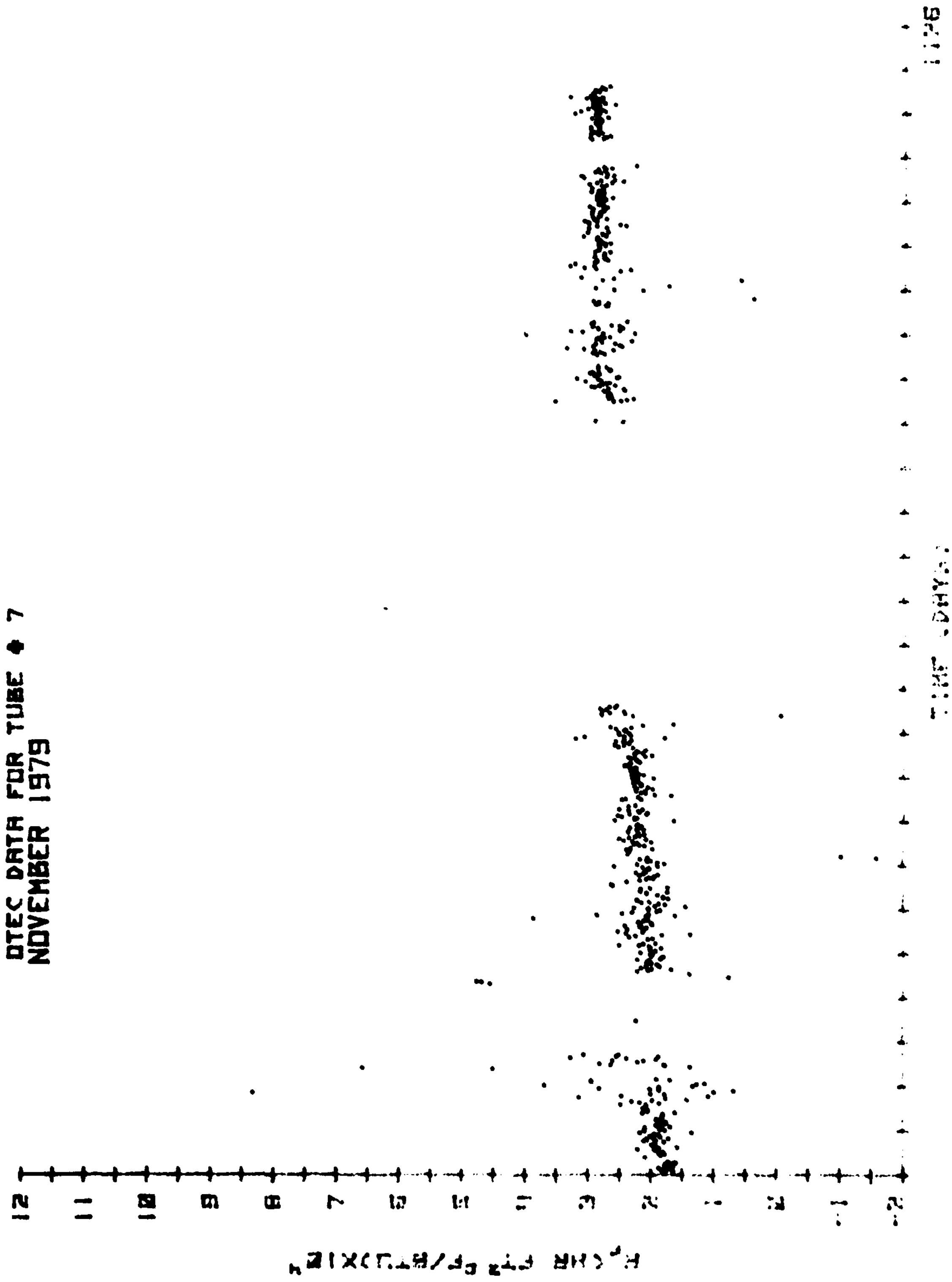


FIGURE E-3.

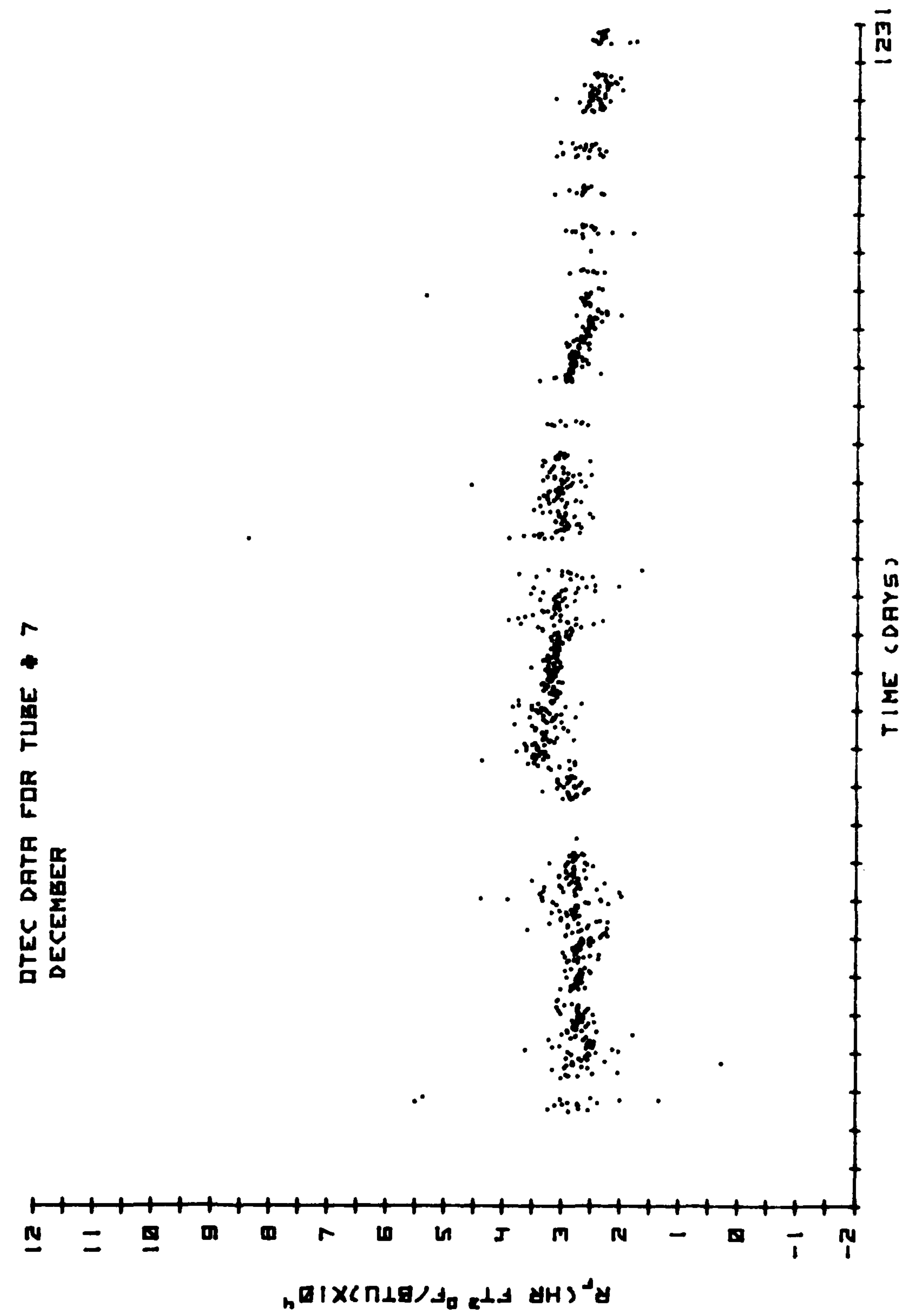

DTEC DATA FOR TUBE # 7
DECEMBER
TIME (DAYS)
123
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE E-4.

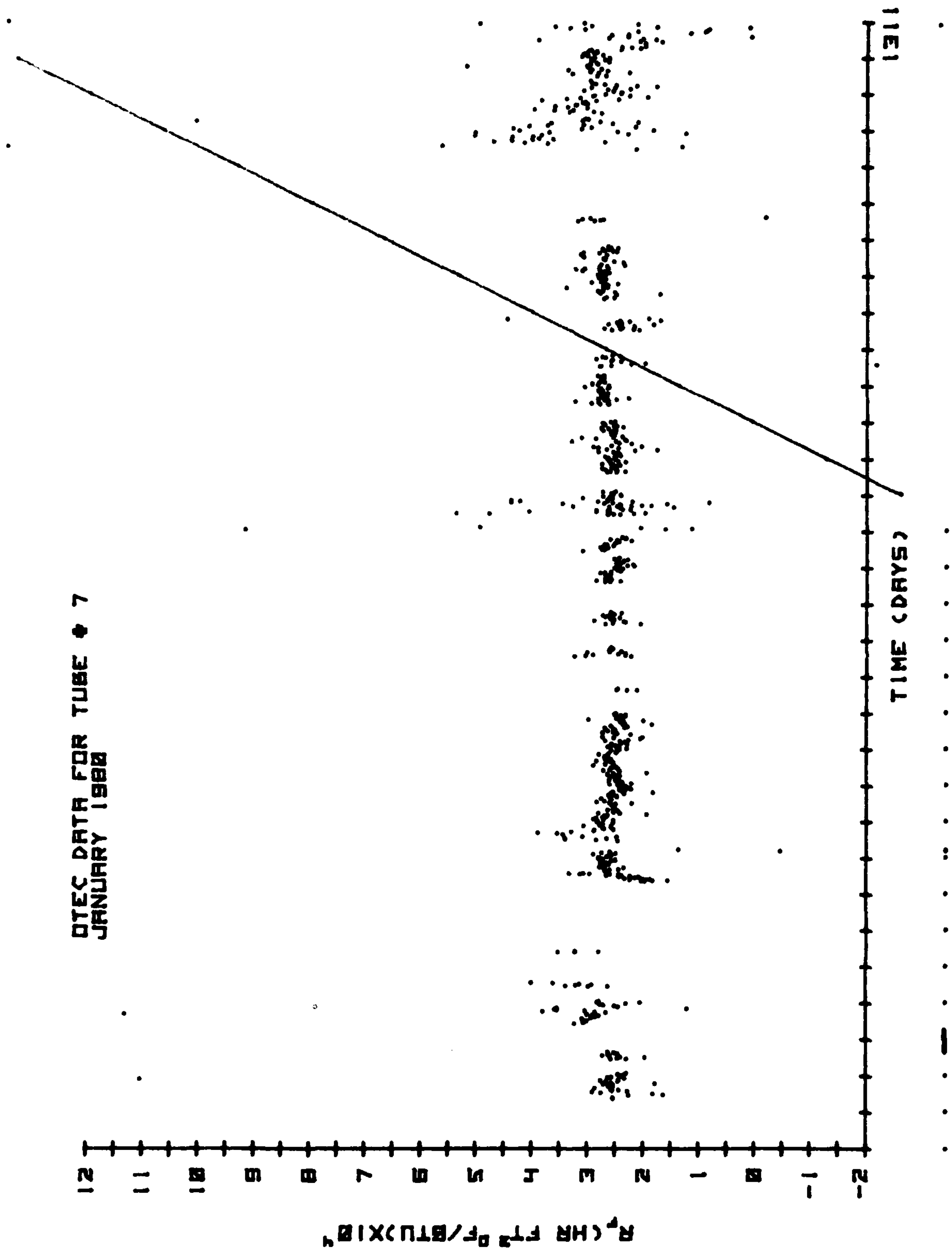

OTEC DATA FOR TUBE # 7
JANUARY 1980
TIME (DAYS)
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
Rf (HR FT2 °F/BTU)X10^4

FIGURE E-5.

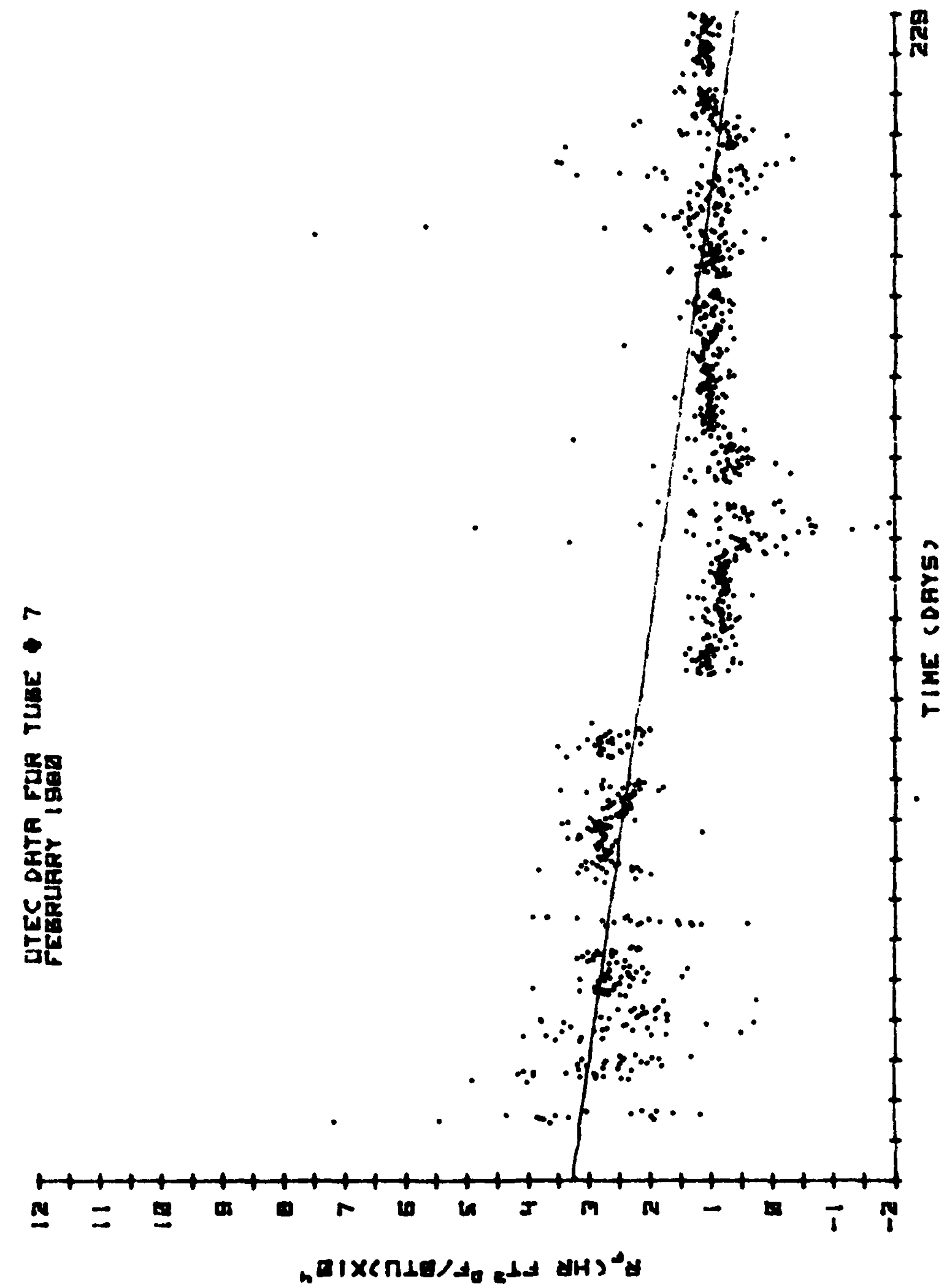

UTEC DATA FOR TUBE # 7
FEBRUARY 1980
TIME (DAYS)
229
R_f,(HR FT² °F/BTU)X10⁴

FIGURE E-6.

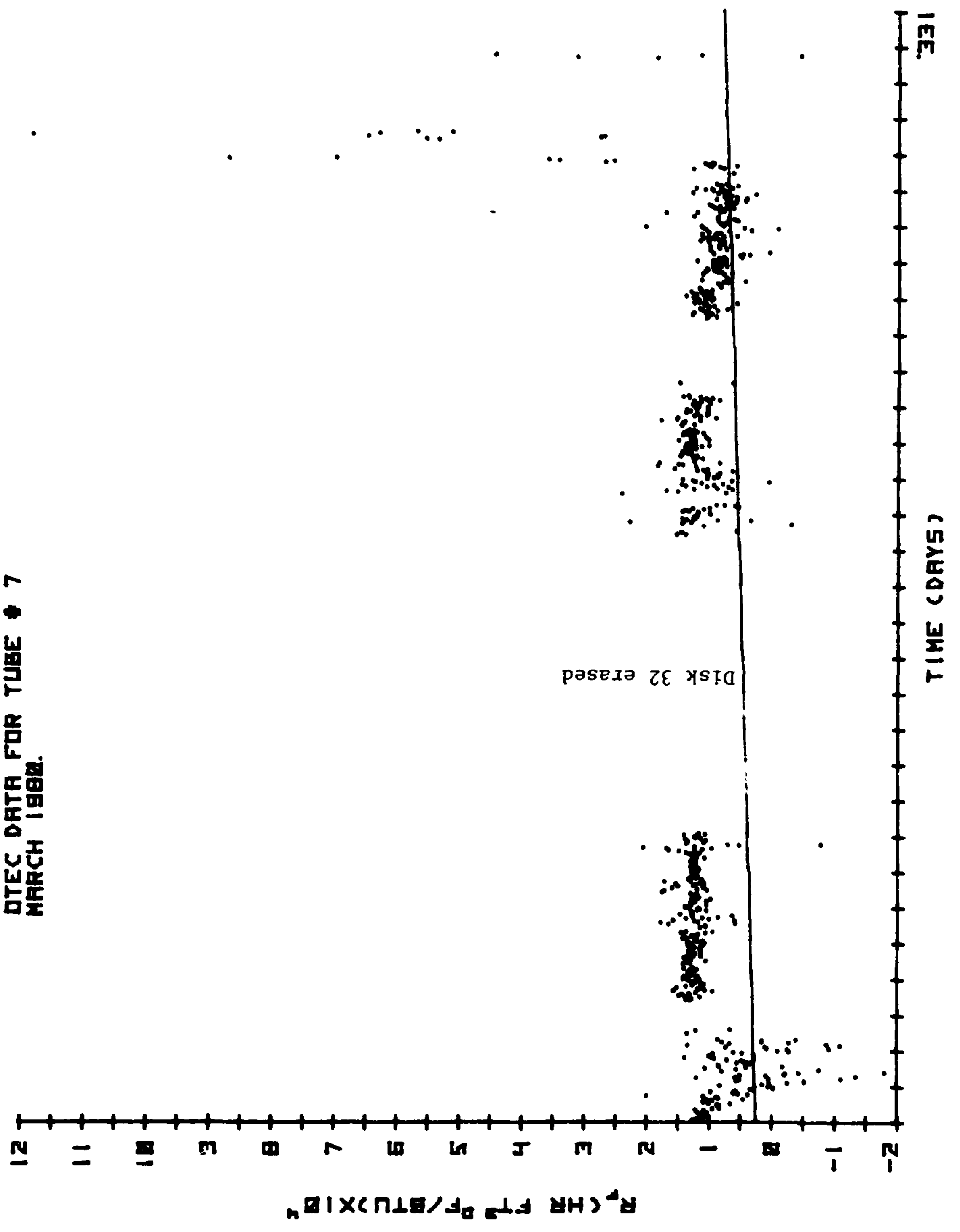

OTEC DATA FOR TUBE # 7
MARCH 1980.
Disk 32 erased
TIME (DAYS)
Rf (HR FT2 °F/BTU)X10^4
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE E-7.

APPENDIX F

MONTHLY PLOTS OF Rf IN TITANIUM PIPE USING RECIRCULATING SPONGE RUBBER BALLS

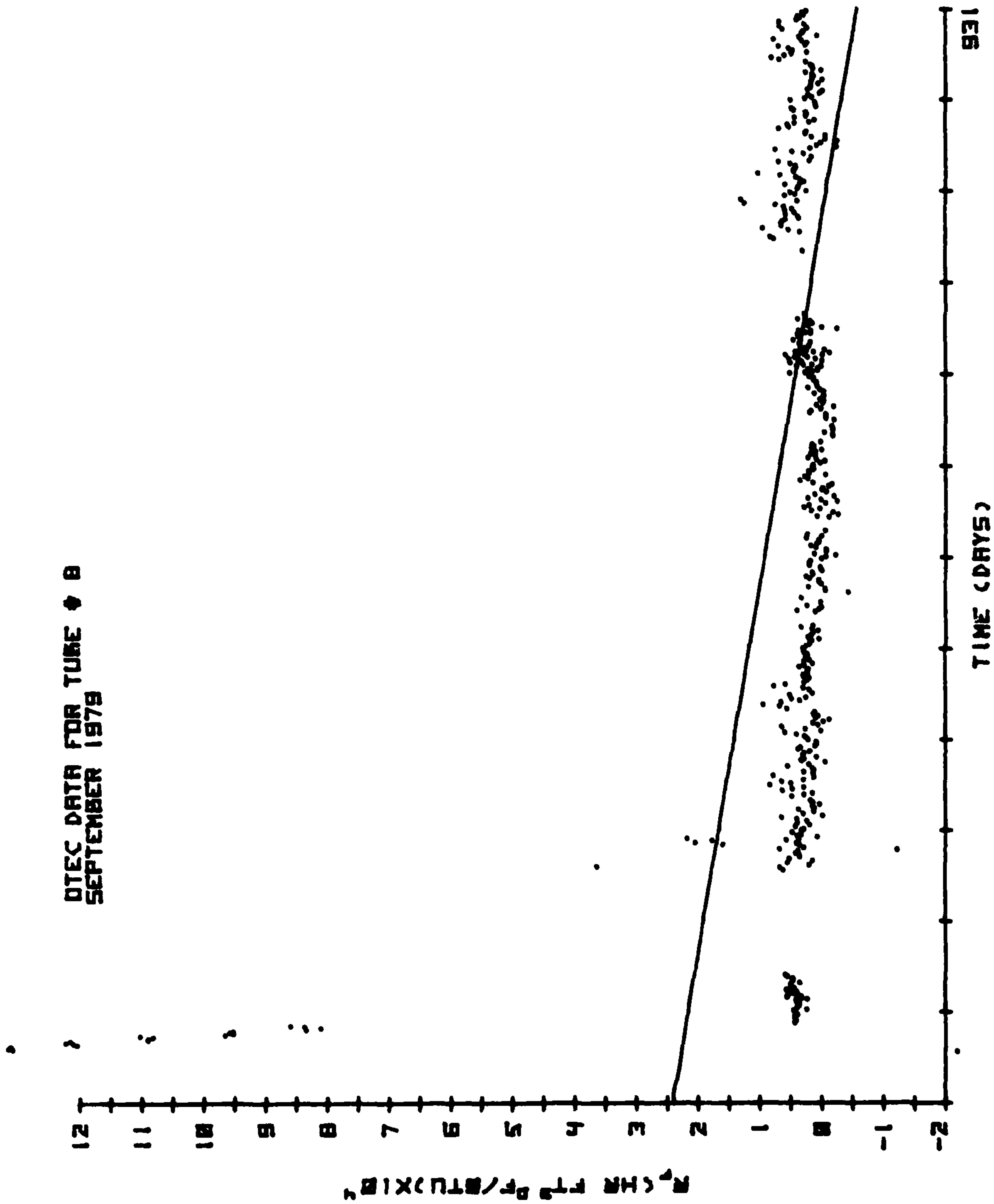

DTEC DATA FOR TUBE # 8
SEPTEMBER 1979
TIME (DAYS)
931
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE F-1.

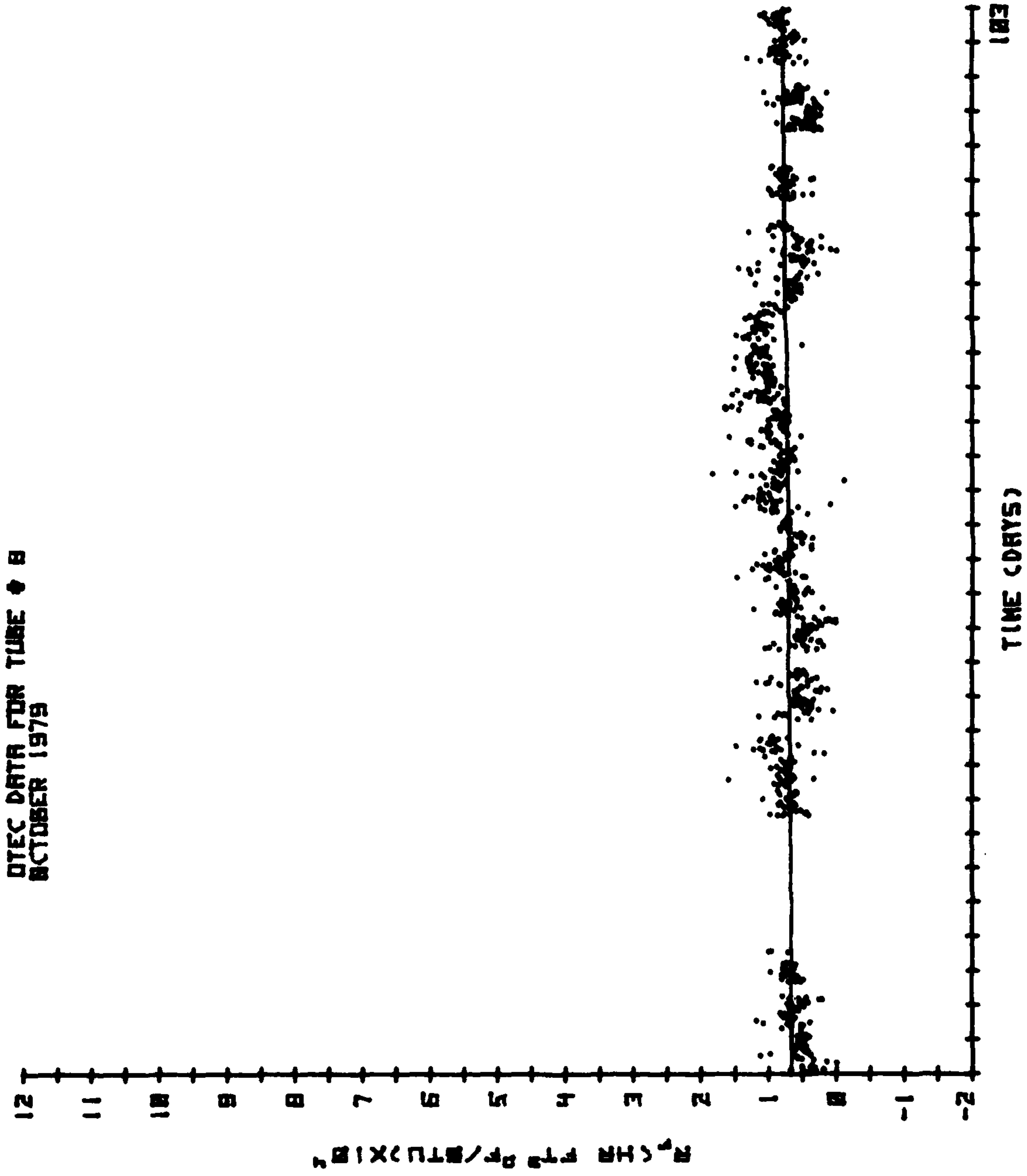


FIGURE F-2.

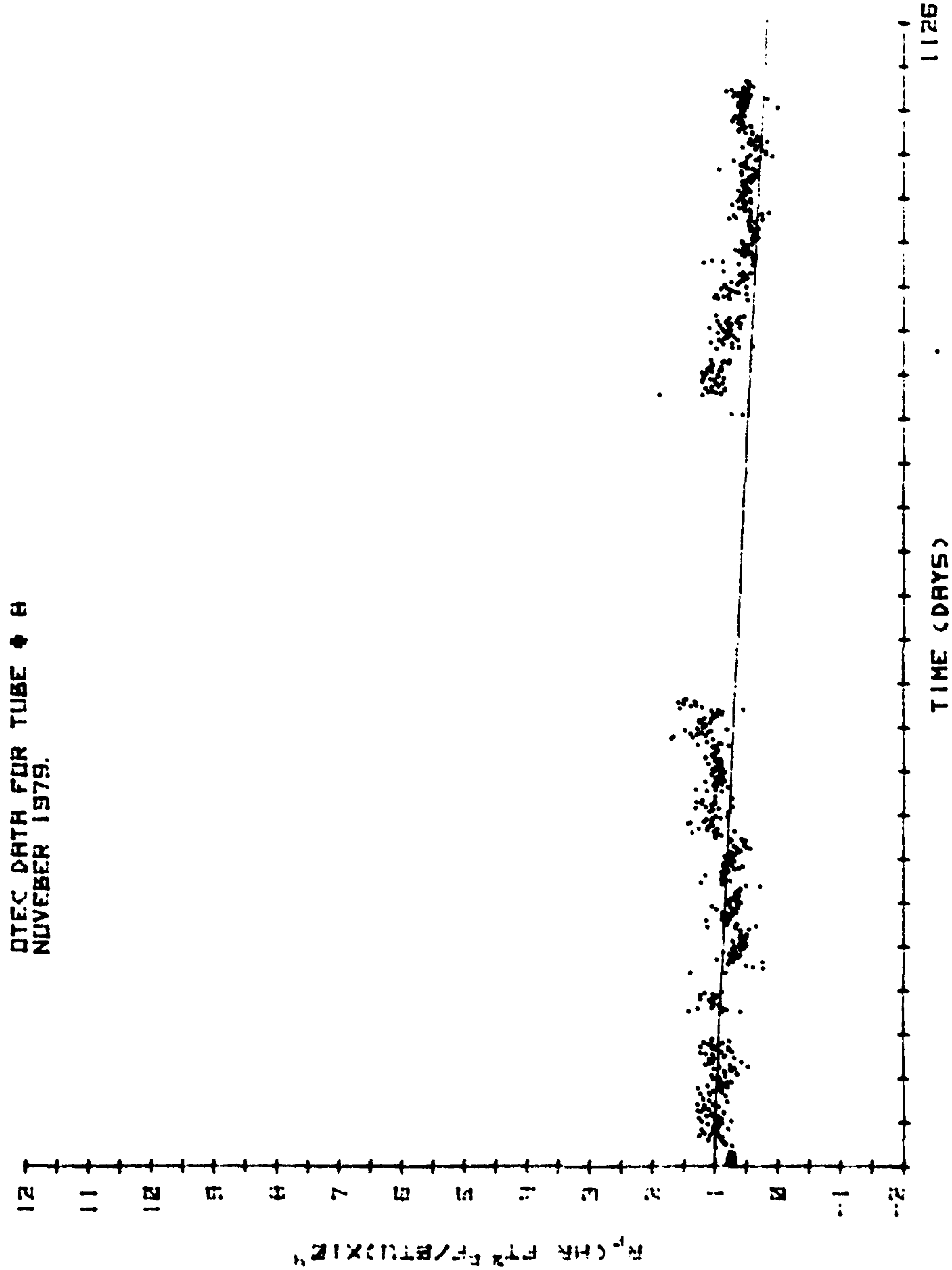


FIGURE F-3.

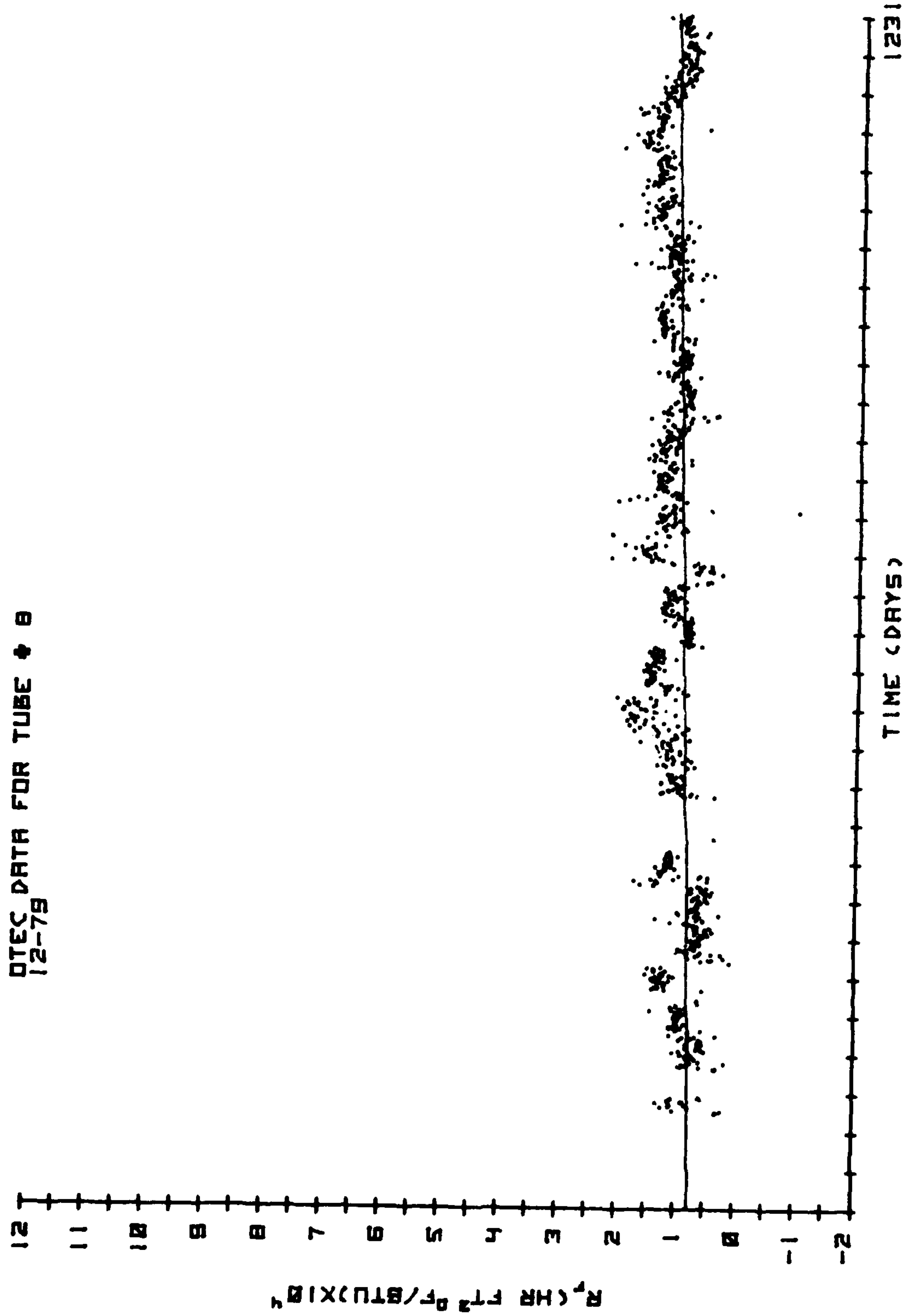

OTEC DATA FOR TUBE # 8
12-79
TIME (DAYS)
123
R_f (HR FT² °F/BTU)X10⁴
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE F-4.

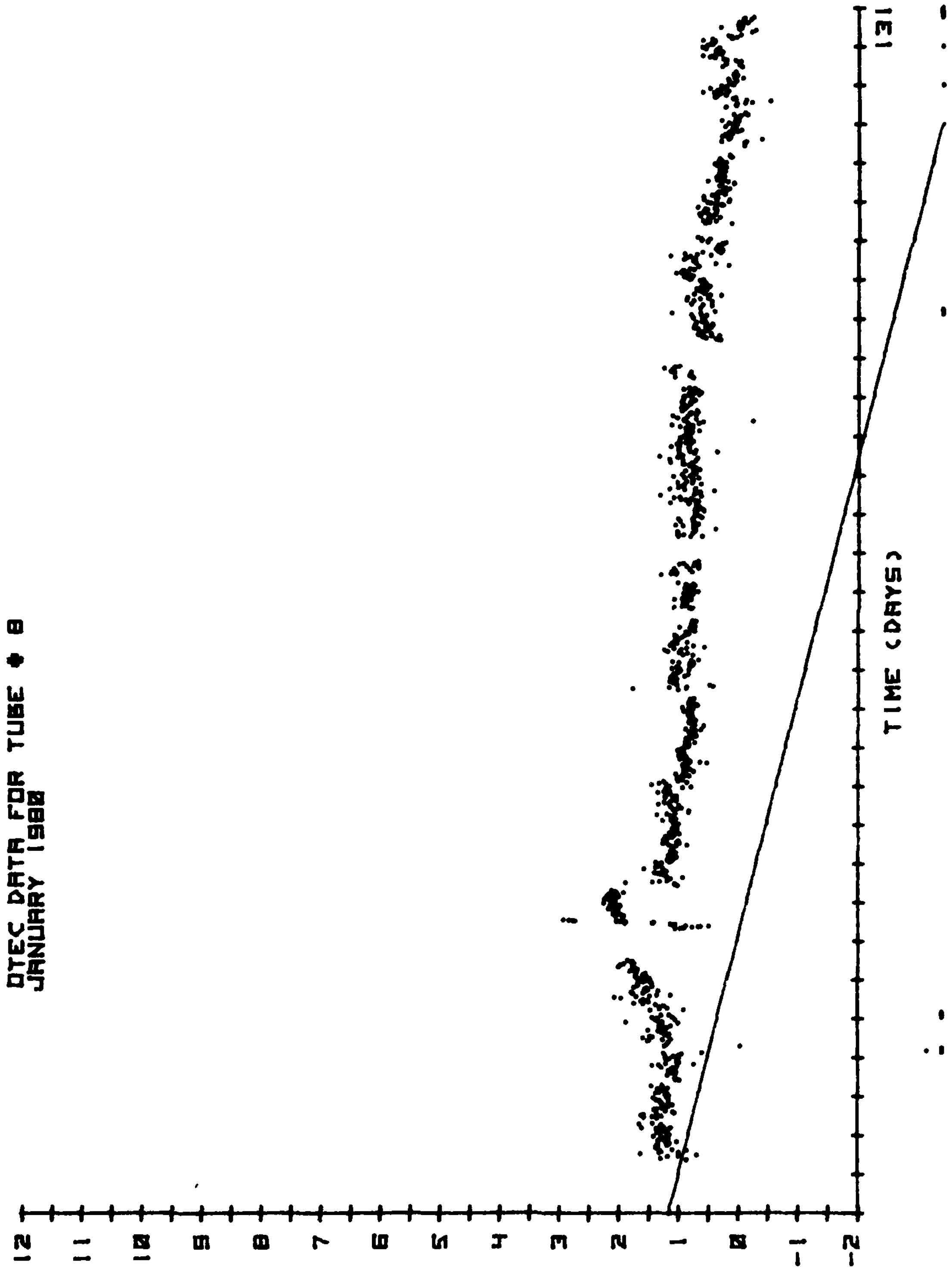

OTEC DATA FOR TUBE # 8
JANUARY 1980
TIME (DAYS)
131
R_f (HR FT² °F/BTU)X10⁴
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE F-5.

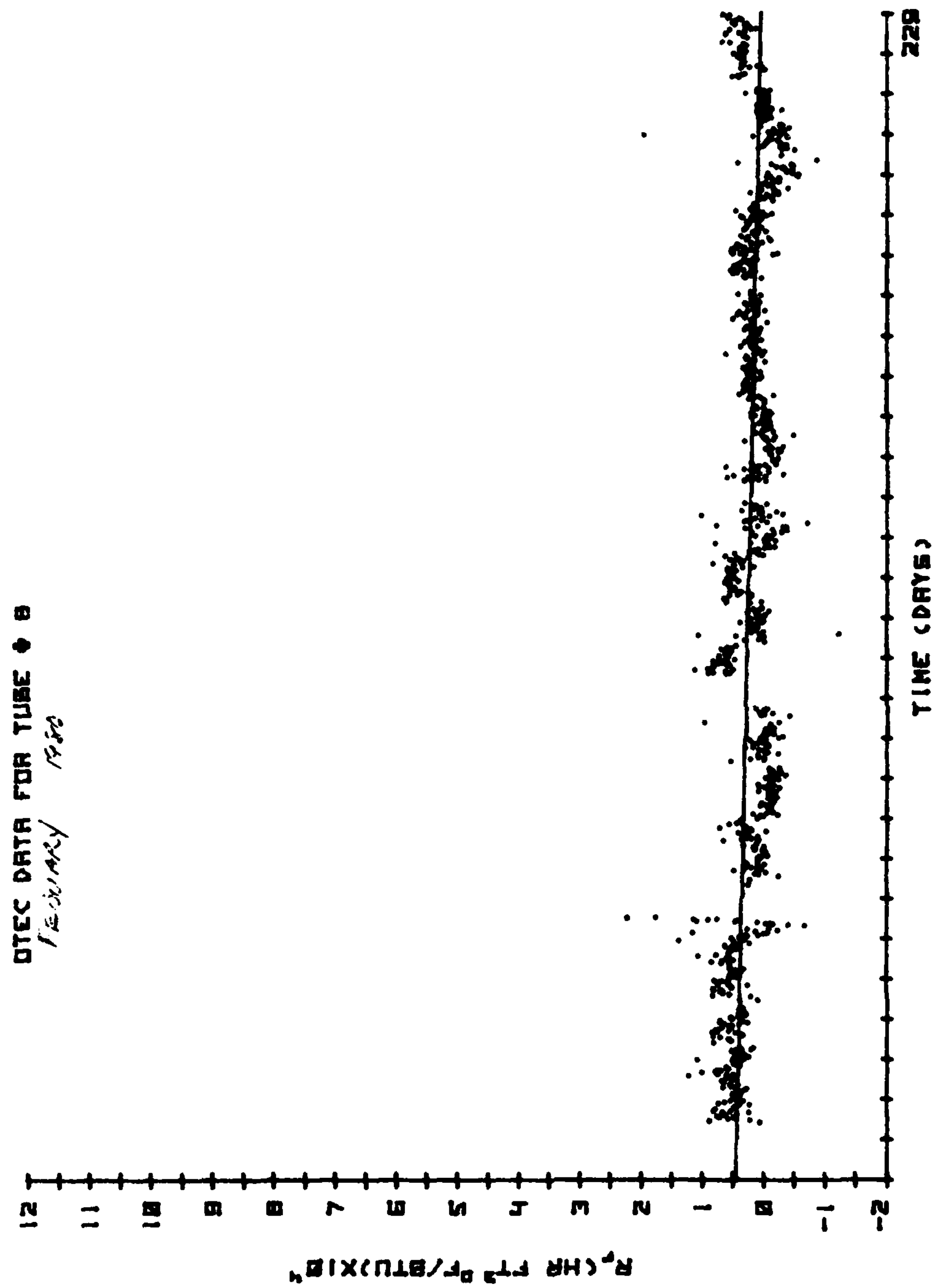

OTEC DATA FOR TUBE # 8
February 1980
TIME (DAYS)
220
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
Rf (HR FT2 °F/BTU)X10^4

FIGURE F-6.

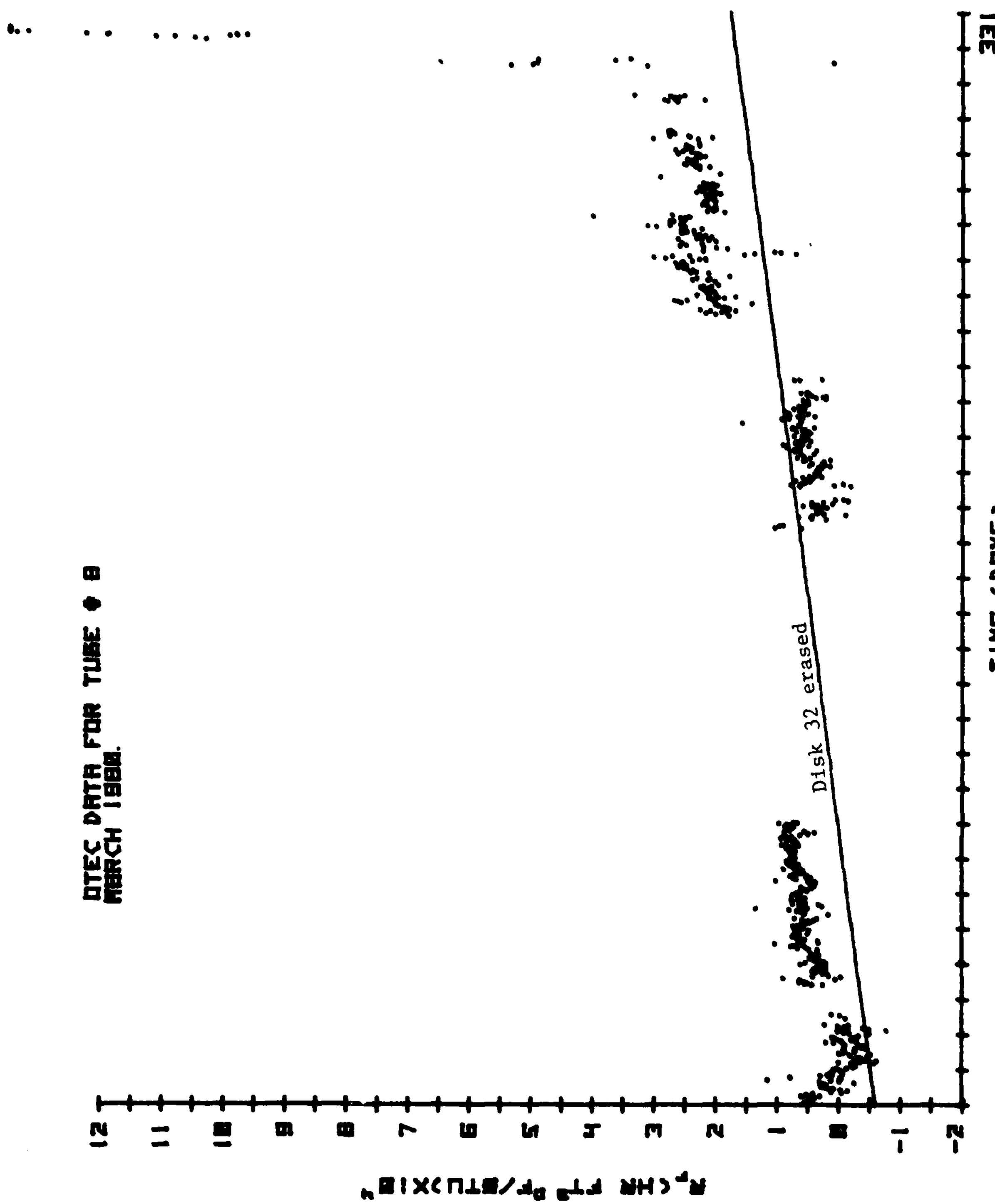

DTEC DATA FOR TUBE # 8
MARCH 1980.
Disk 32 erased
TIME (DAYS)
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE F-7.

APPENDIX G

MONTHLY PLOTS OF Rf IN ALUMINUM PIPE SUBJECT TO CHLORINATION

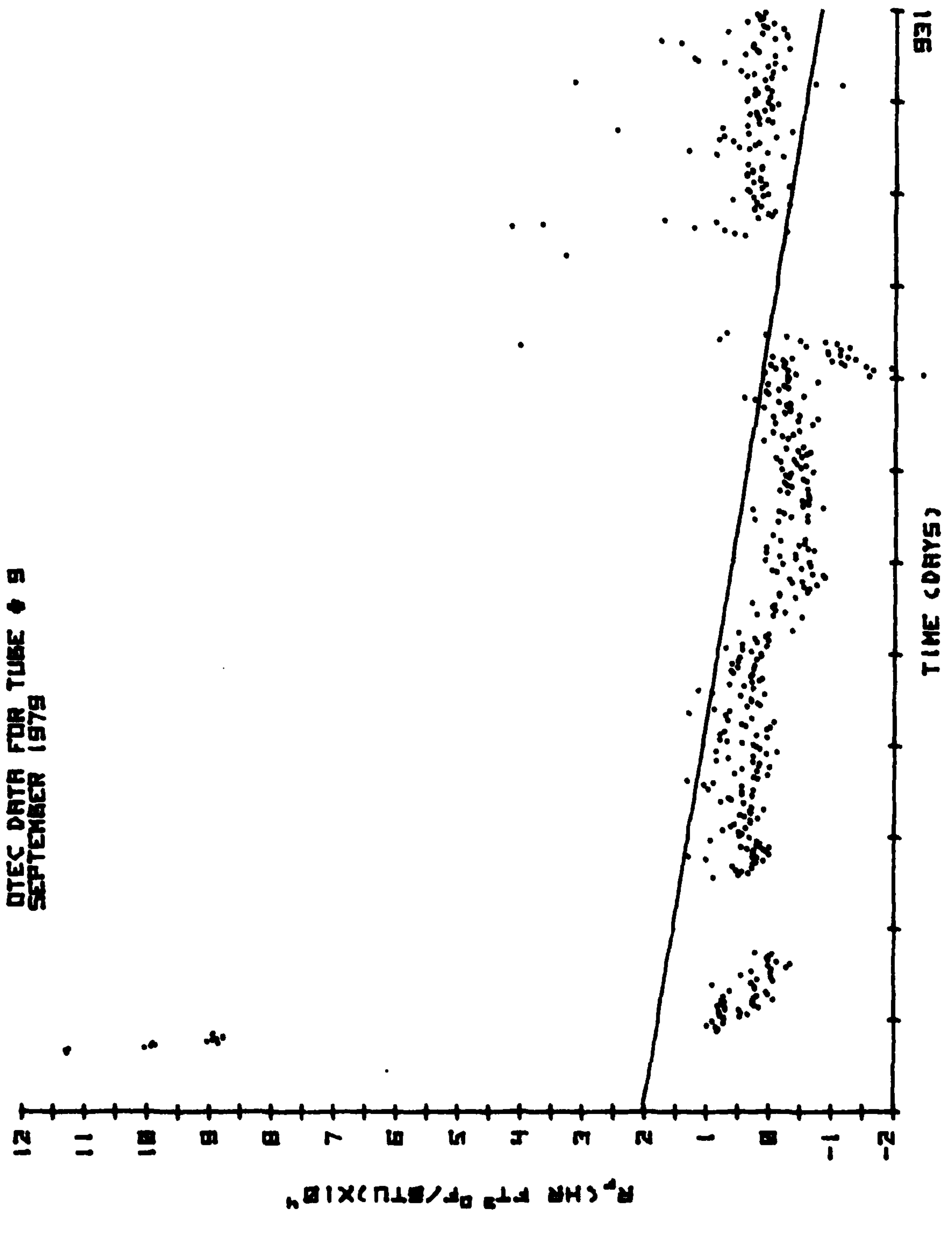

OTEC DATA FOR TUBE # 9
SEPTEMBER 1979
TIME (DAYS)
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
186

FIGURE G-1.

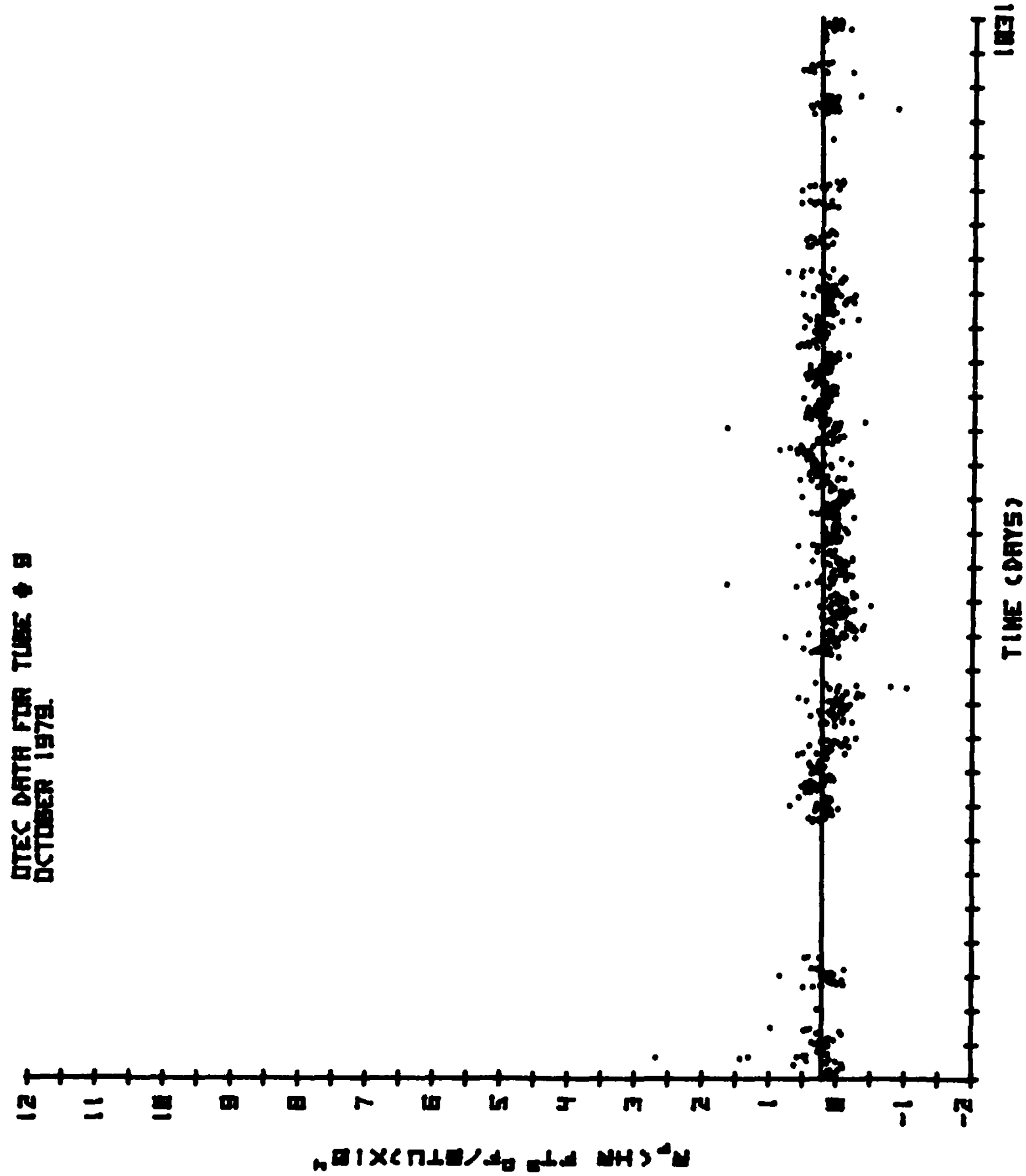

OTEC DATA FOR TUBE #
OCTOBER 1979.
TIME (DAYS)
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE G-2.

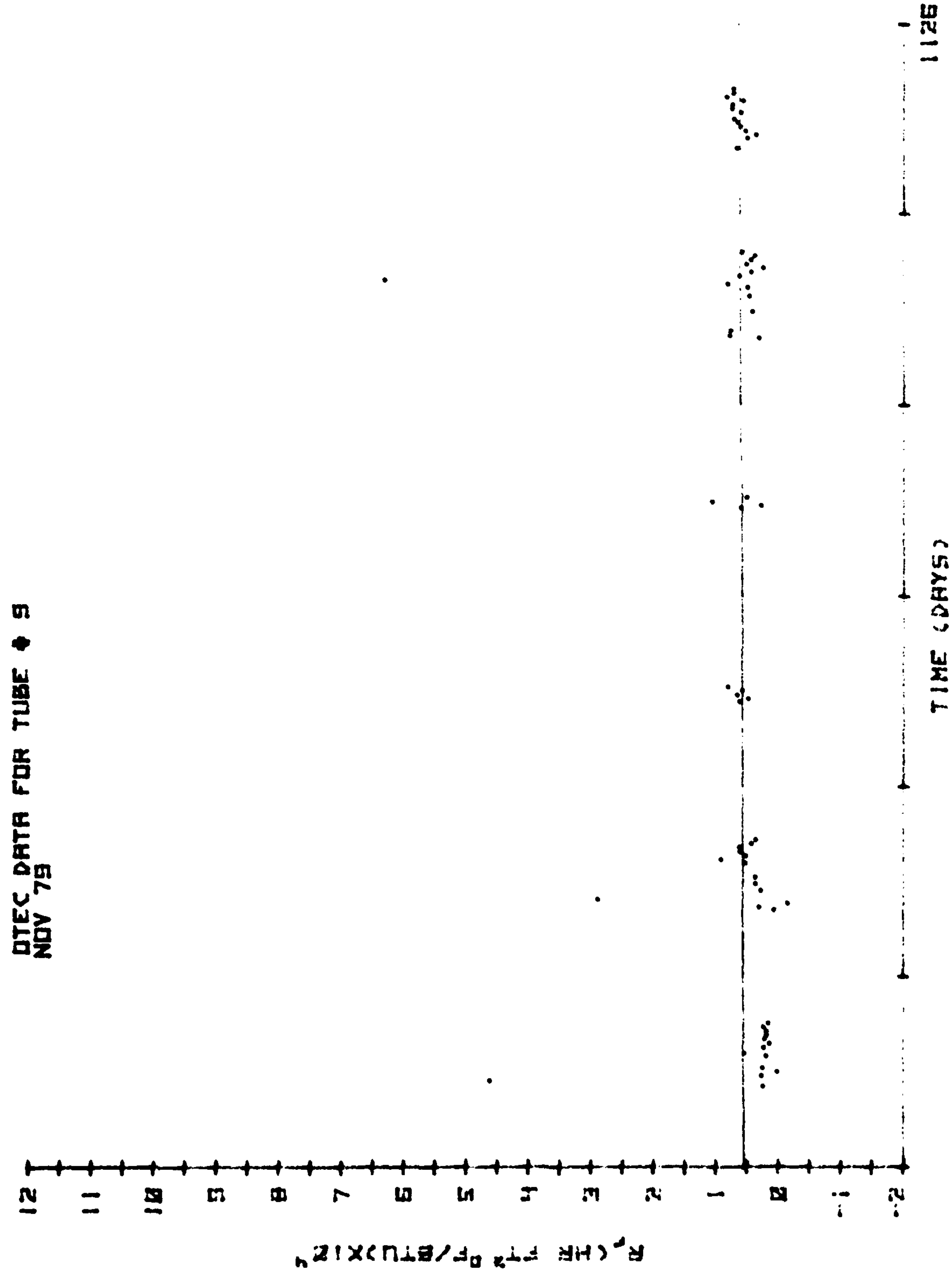

DTEC DATA FOR TUBE # 9
NOV 79
TIME (DAYS)
1126
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE G-3.

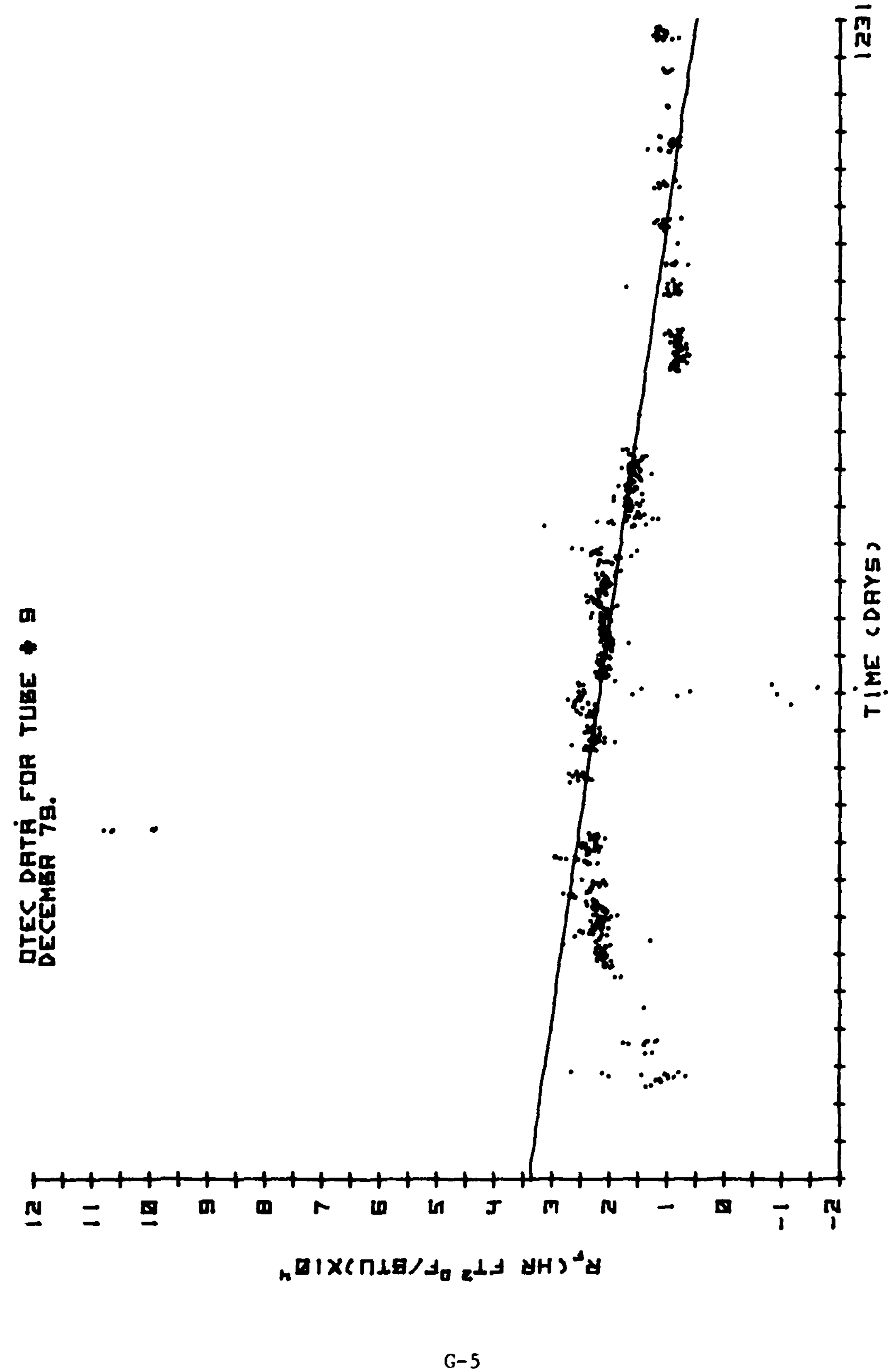

OTEC DATA FOR TUBE # 9
DECEMBER 79.
TIME (DAYS)
123
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE G-4.

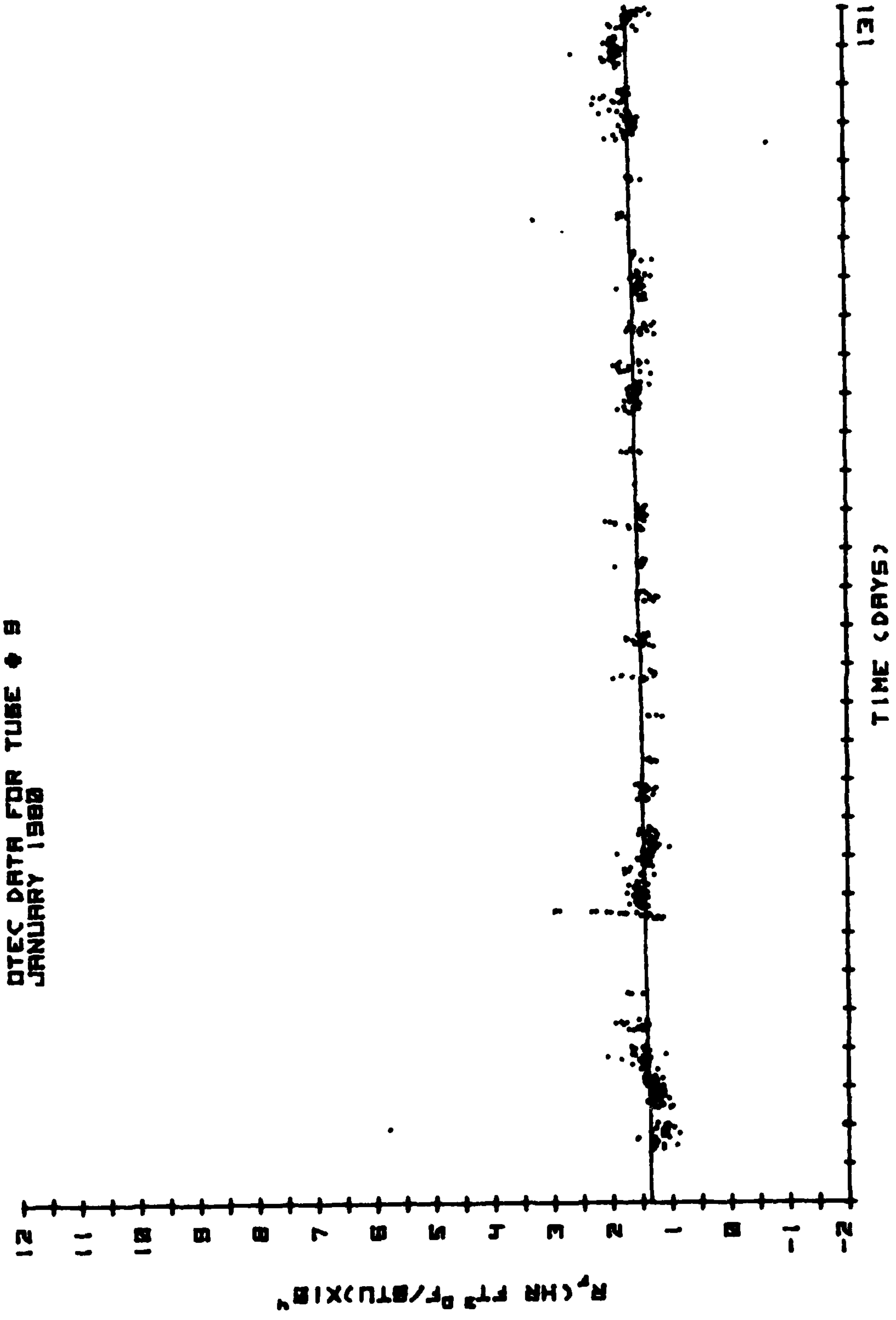

OTEC DATA FOR TUBE # 9
JANUARY 1980
TIME (DAYS)
131
R_f (HR FT^2 °F/BTU)X10^4
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE G-5.

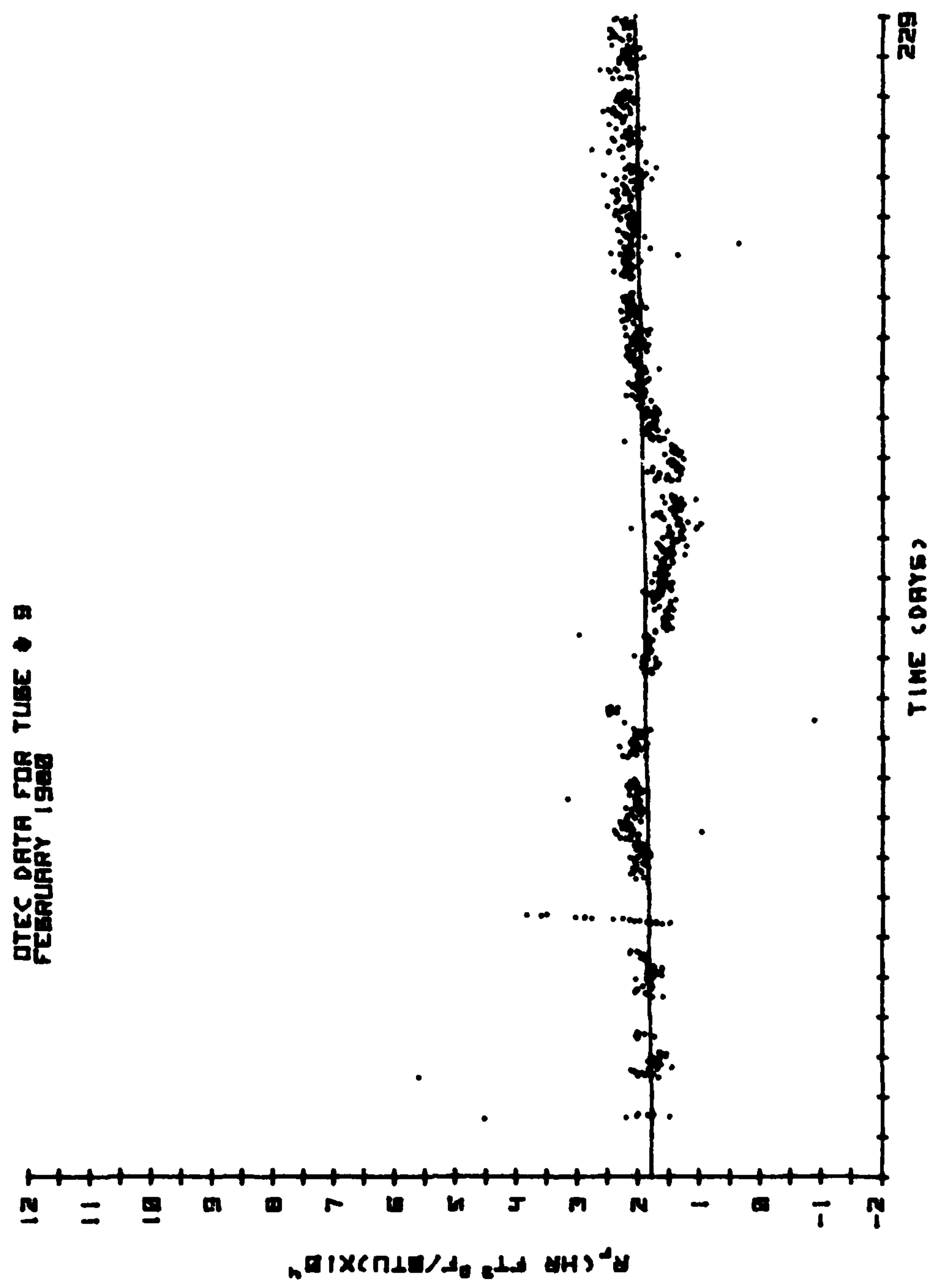

OTEC DATA FOR TUBE # 9
FEBRUARY 1980
TIME (DAYS)
229
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE G-6.

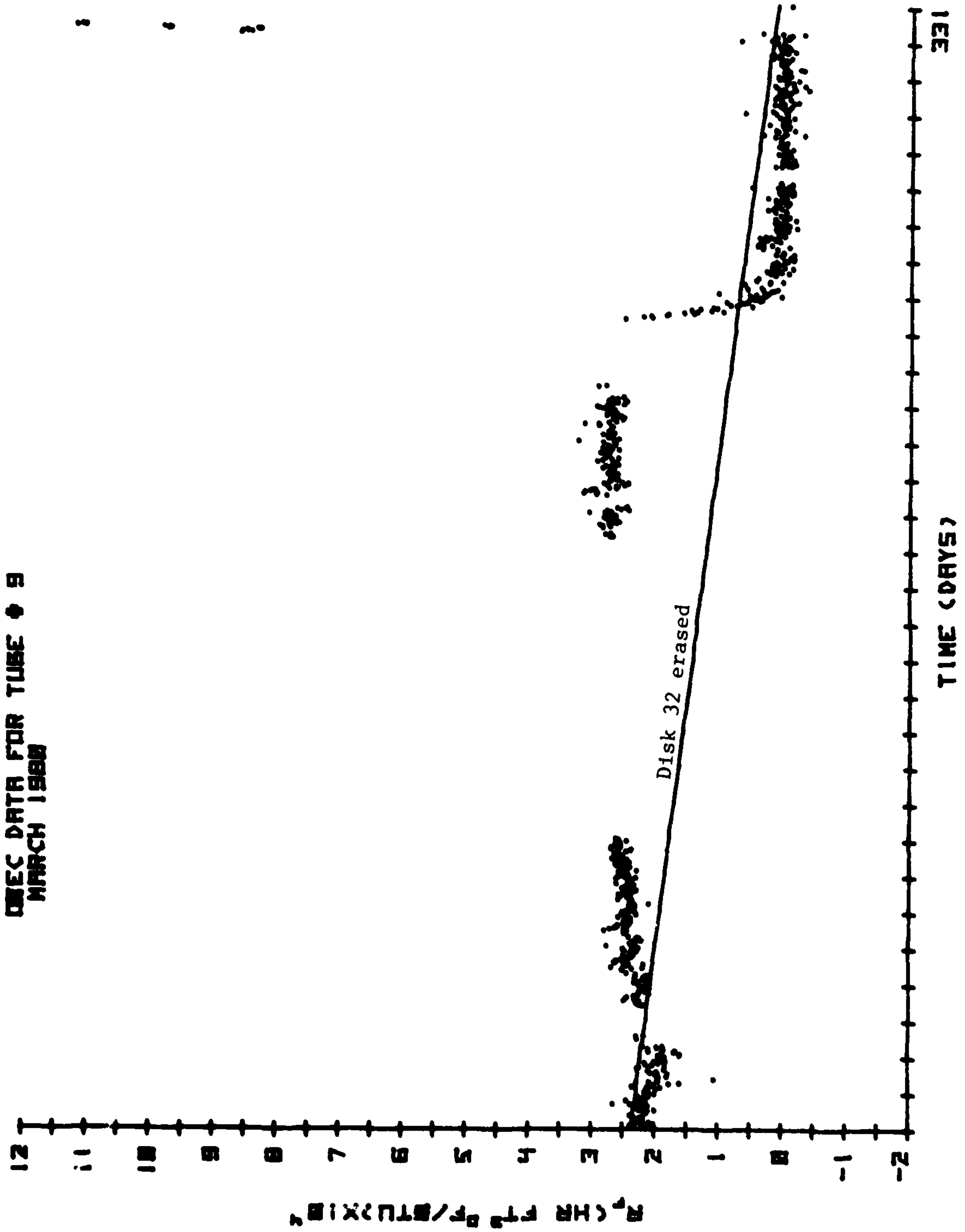

DATA FOR TUBE # 9
MARCH 1980
Disk 32 erased
TIME (DAYS)
331
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE G-7.

APPENDIX H

MONTHLY PLOTS OF Rf IN TITANIUM PIPE SUBJECT TO CHLORINATION

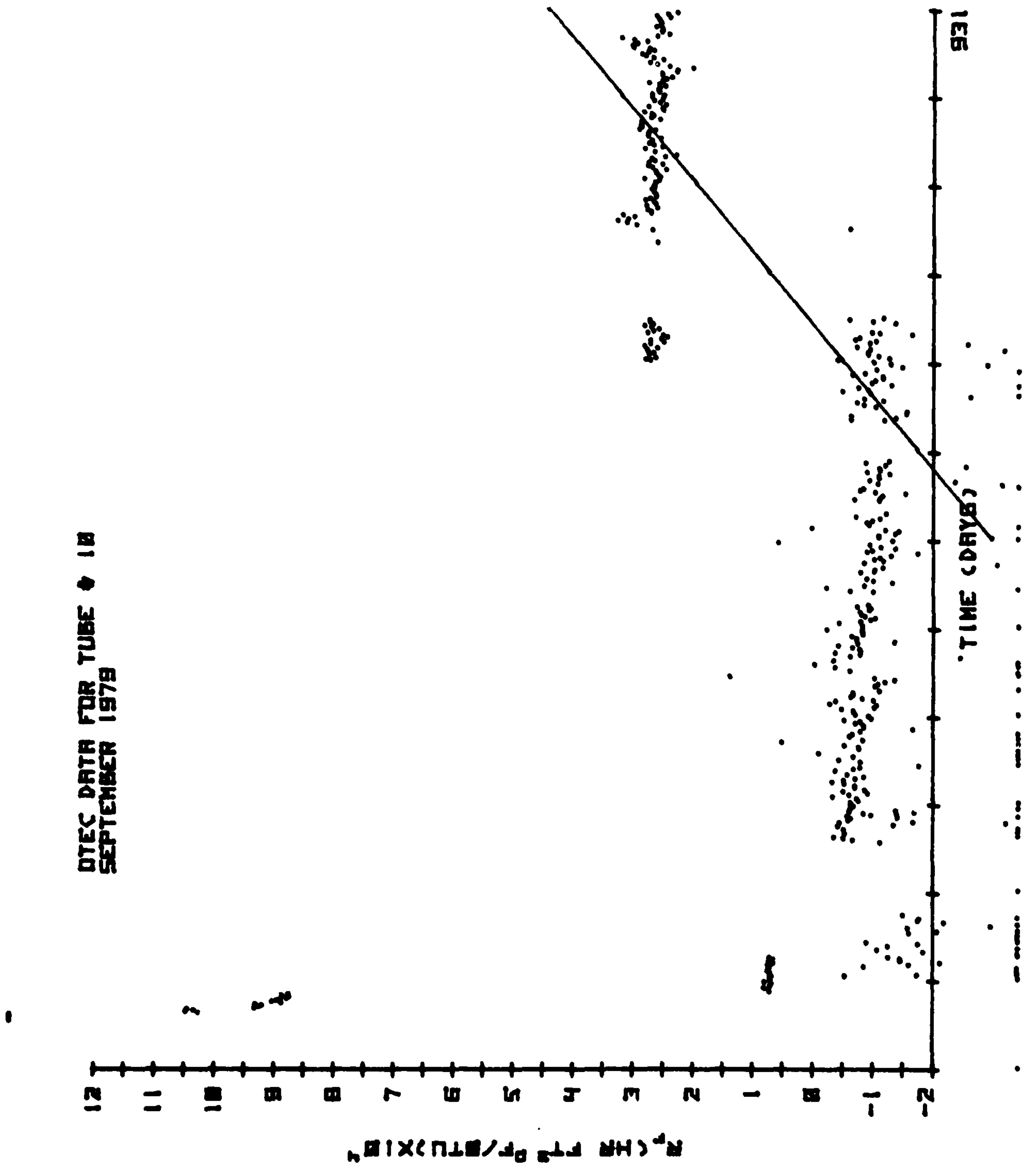

OTEC DATA FOR TUBE # 10
SEPTEMBER 1979
TIME (DAYS)
R_f (HR FT² °F/BTU)X10⁴
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE H-1.

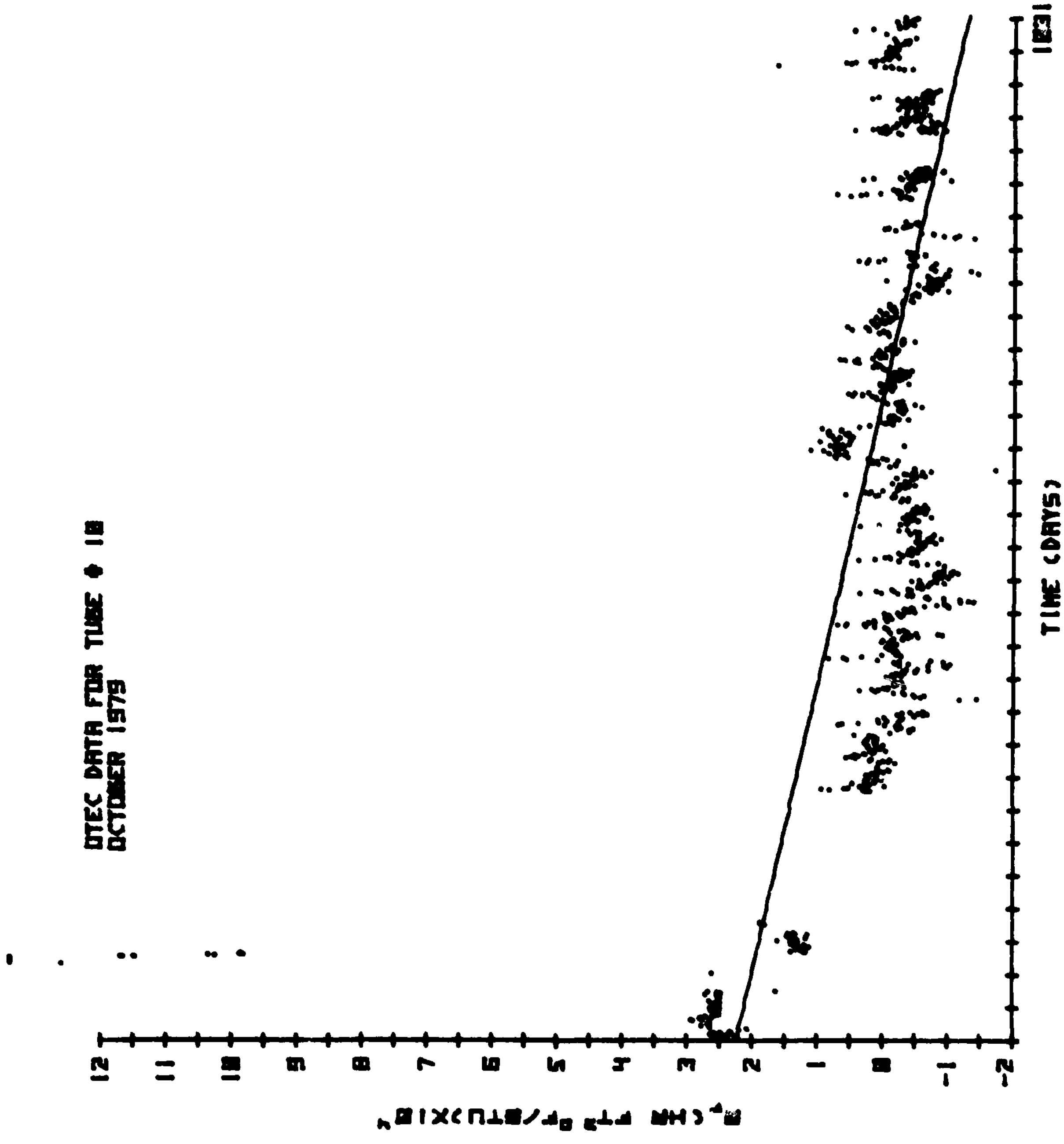

OTEC DATA FOR TUBE # 18
OCTOBER 1979
TIME (DAYS)
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE H-2.

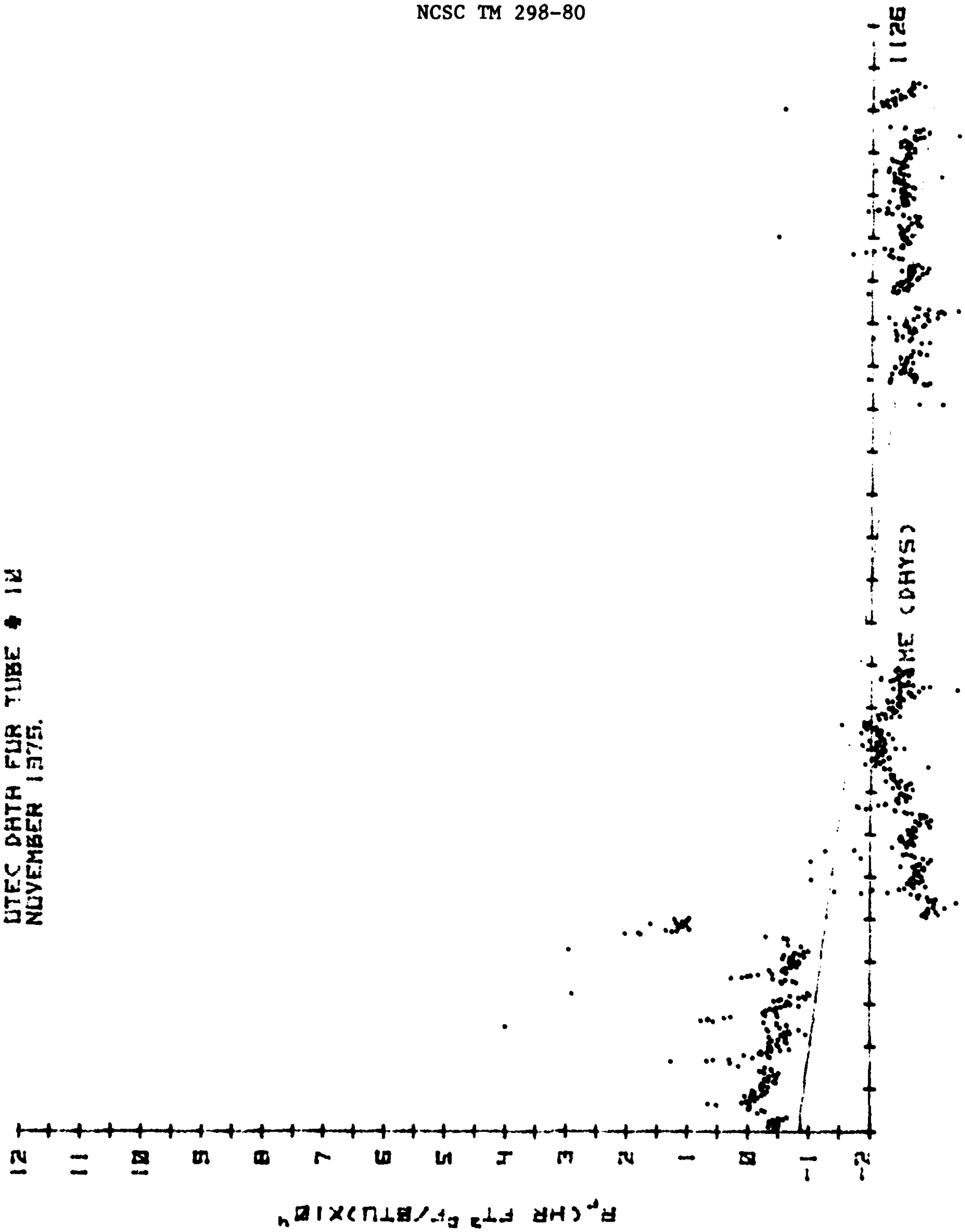

UTEC DATA FOR TUBE # 12
NOVEMBER 1975.
TIME (DAYS)
1126
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE H-3.

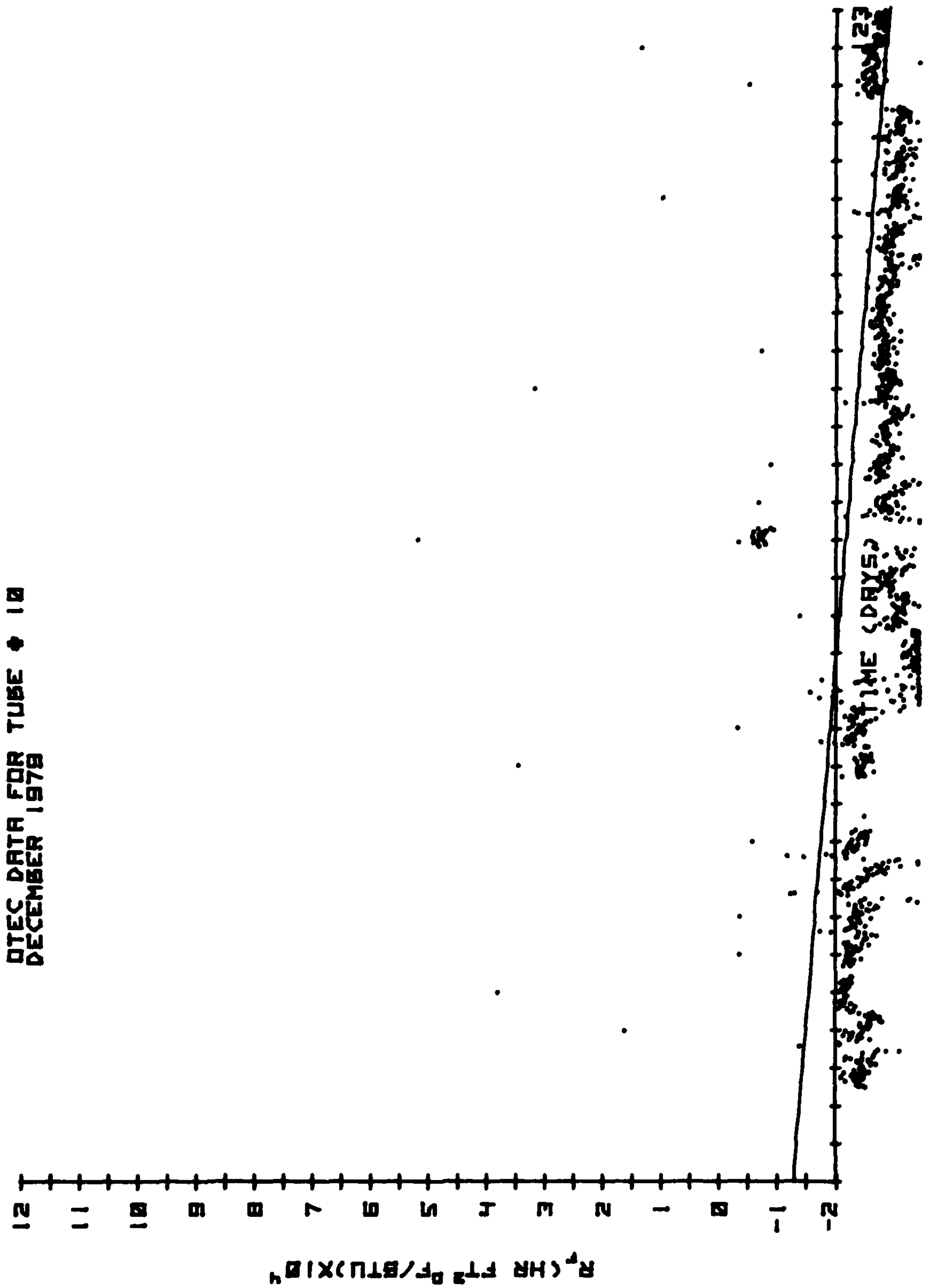

OTEC DATA FOR TUBE # 10
DECEMBER 1979
TIME (DAYS)
231
R_f (HR FT^2 °F/BTU)X10^4
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE H-4.

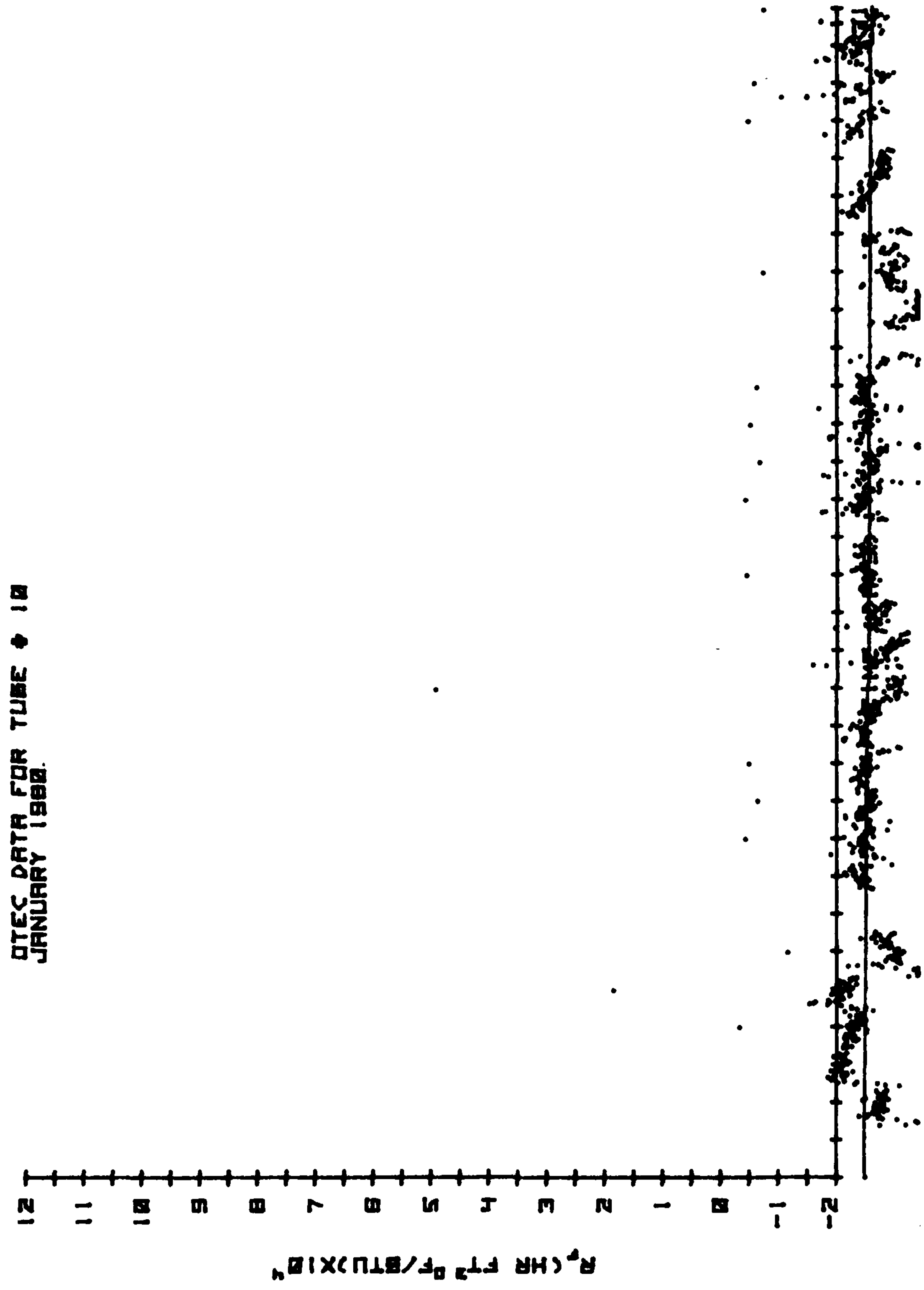

OTEC DATA FOR TUBE # 10
JANUARY 1980
R (HR FT °F/BTU)X10
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE H-5.

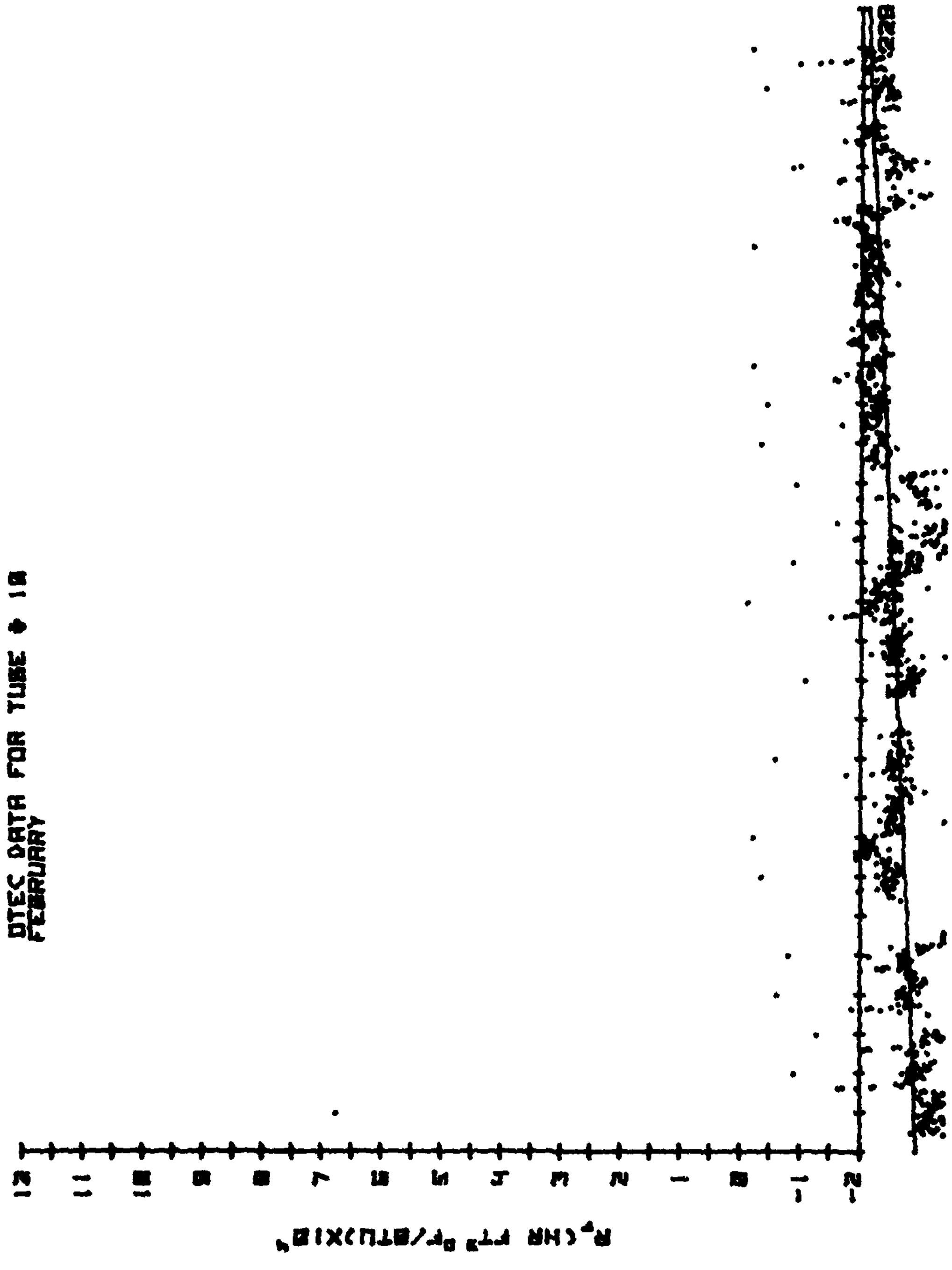


FIGURE H-6.

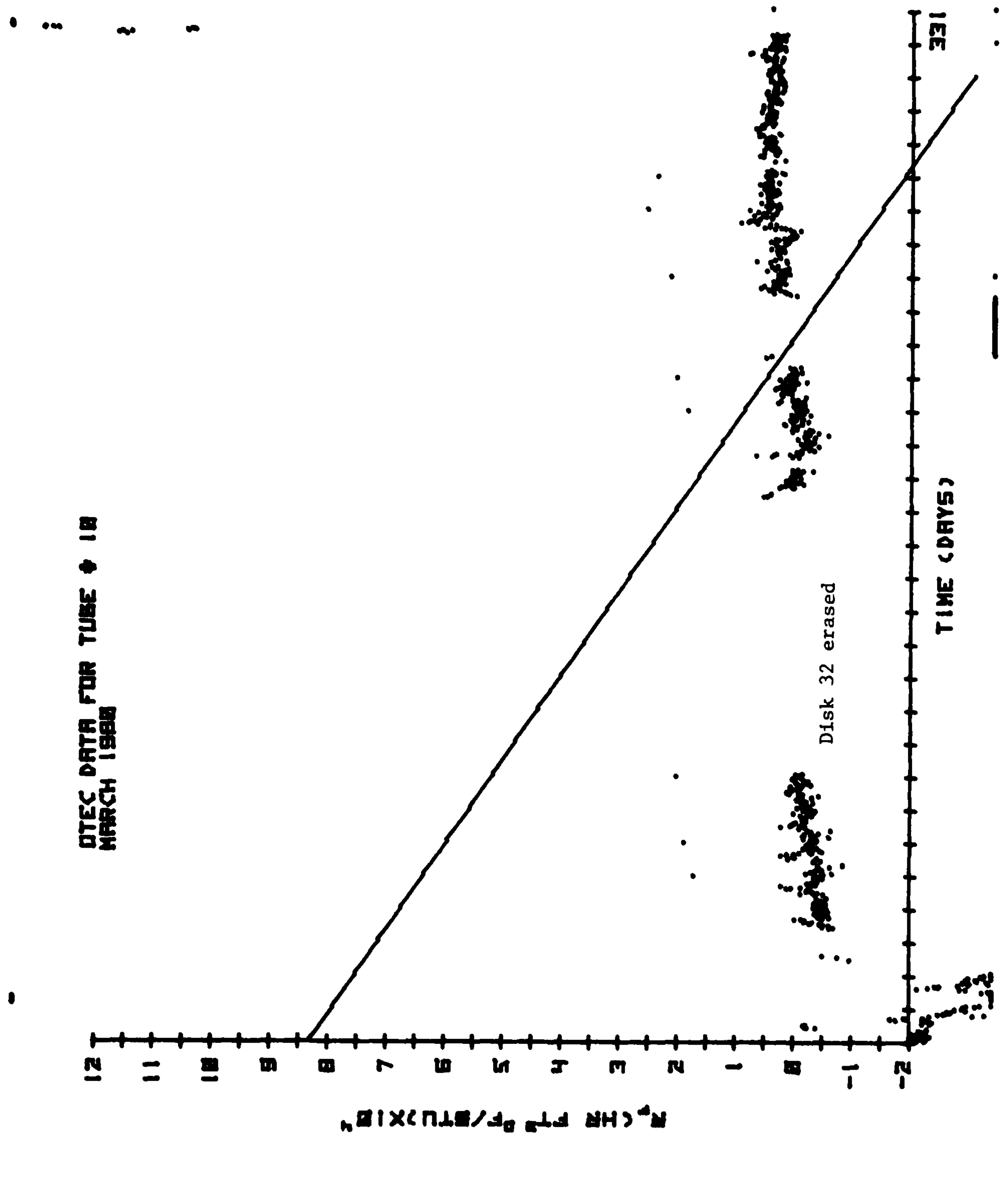

OTEC DATA FOR TUBE # 10
MARCH 1980
R_f (HR FT² °F/BTU)X10⁴
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
TIME (DAYS)
331
Disk 32 erased

FIGURE H-7.

APPENDIX I

MONTHLY PLOTS OF Rf OBTAINED IN THE

ALUMINUM CONTROL, CLEANED DAILY

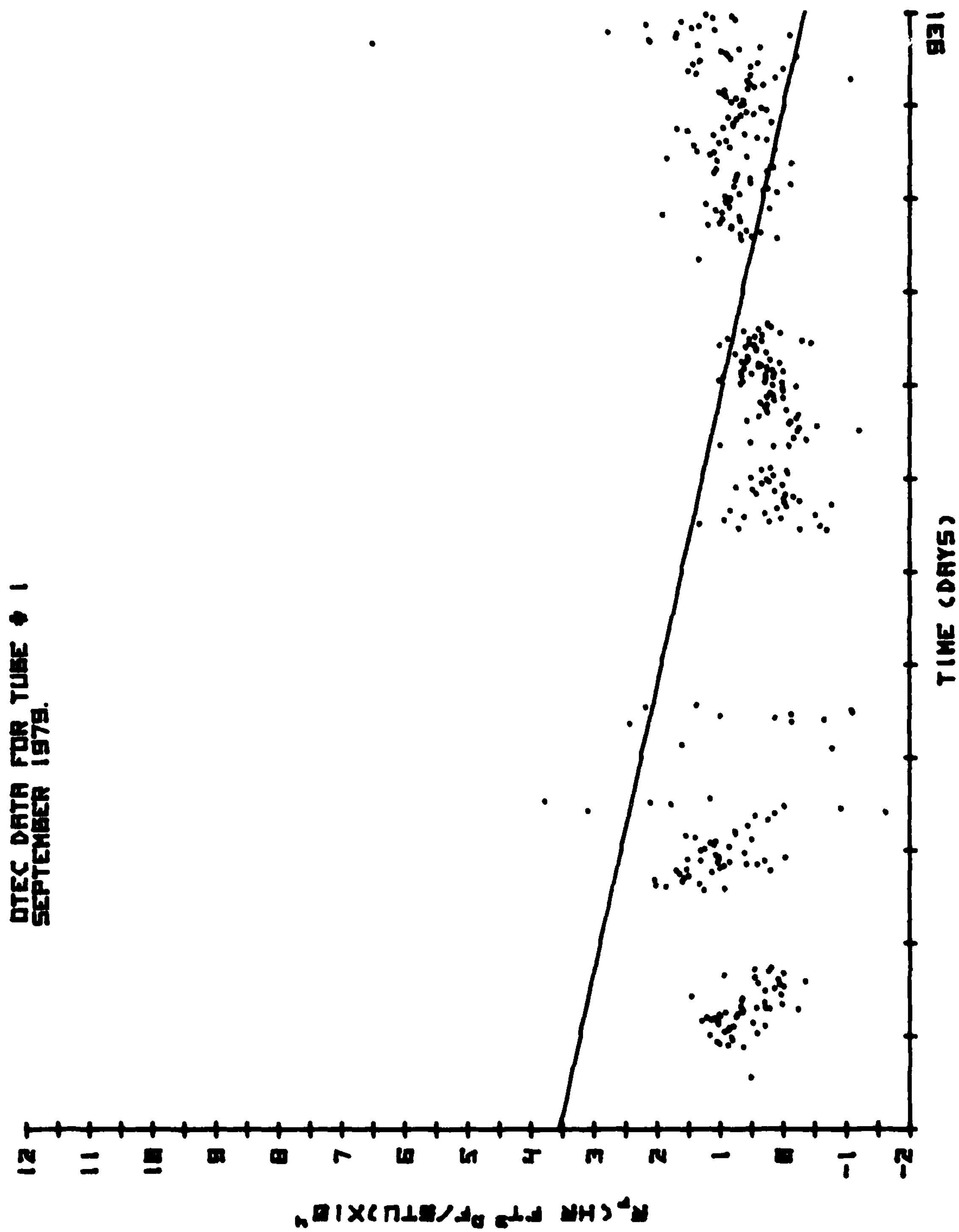

DTEC DATA FOR TUBE # 1
SEPTEMBER 1979.
TIME (DAYS)
128
R_f (HR FT^2 °F/BTU)X10^4
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE I-1.

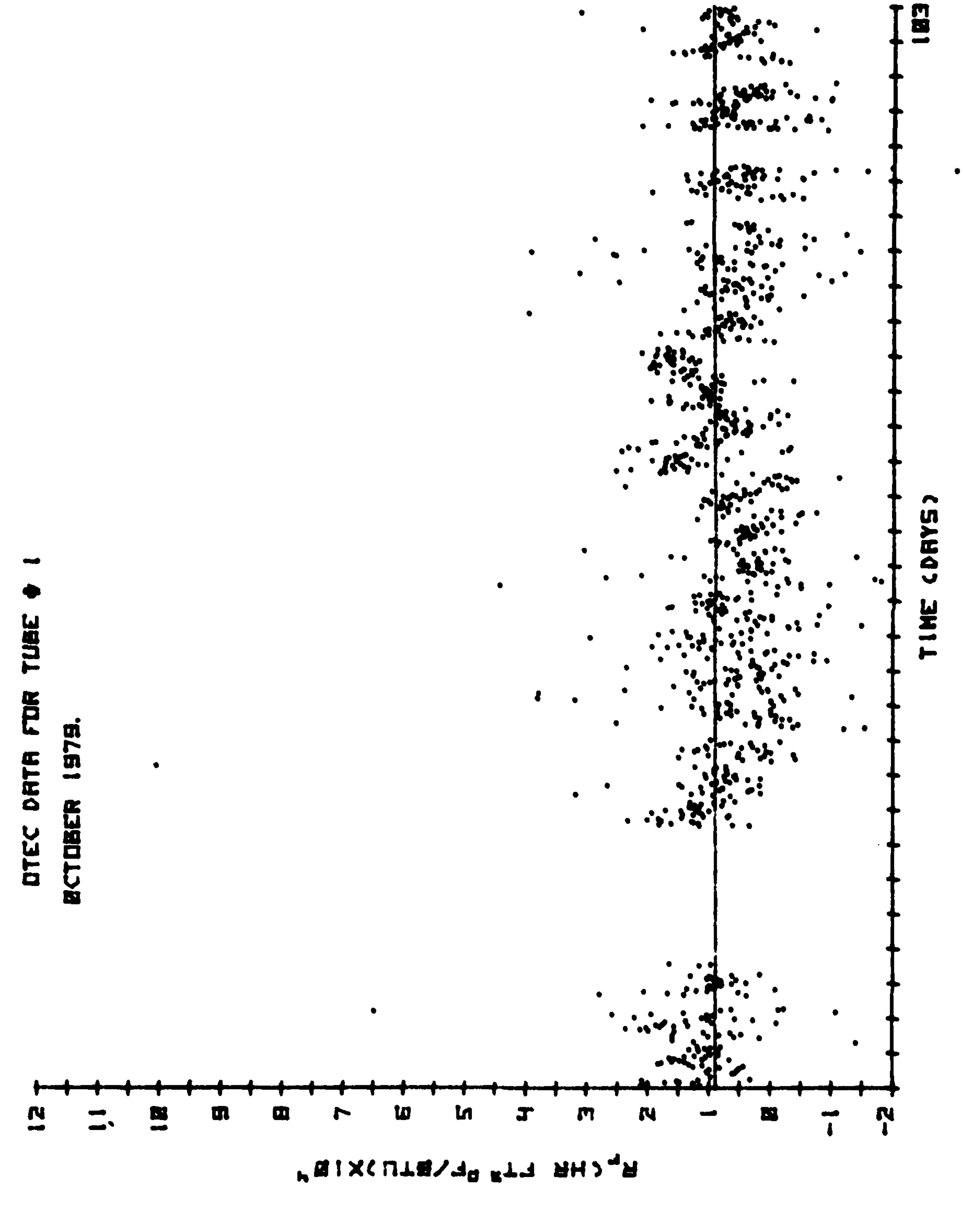

OTEC DATA FOR TUBE # 1
OCTOBER 1979.
TIME (DAYS)
R_f (HR FT² °F/BTU) X 10⁴
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE I-2.

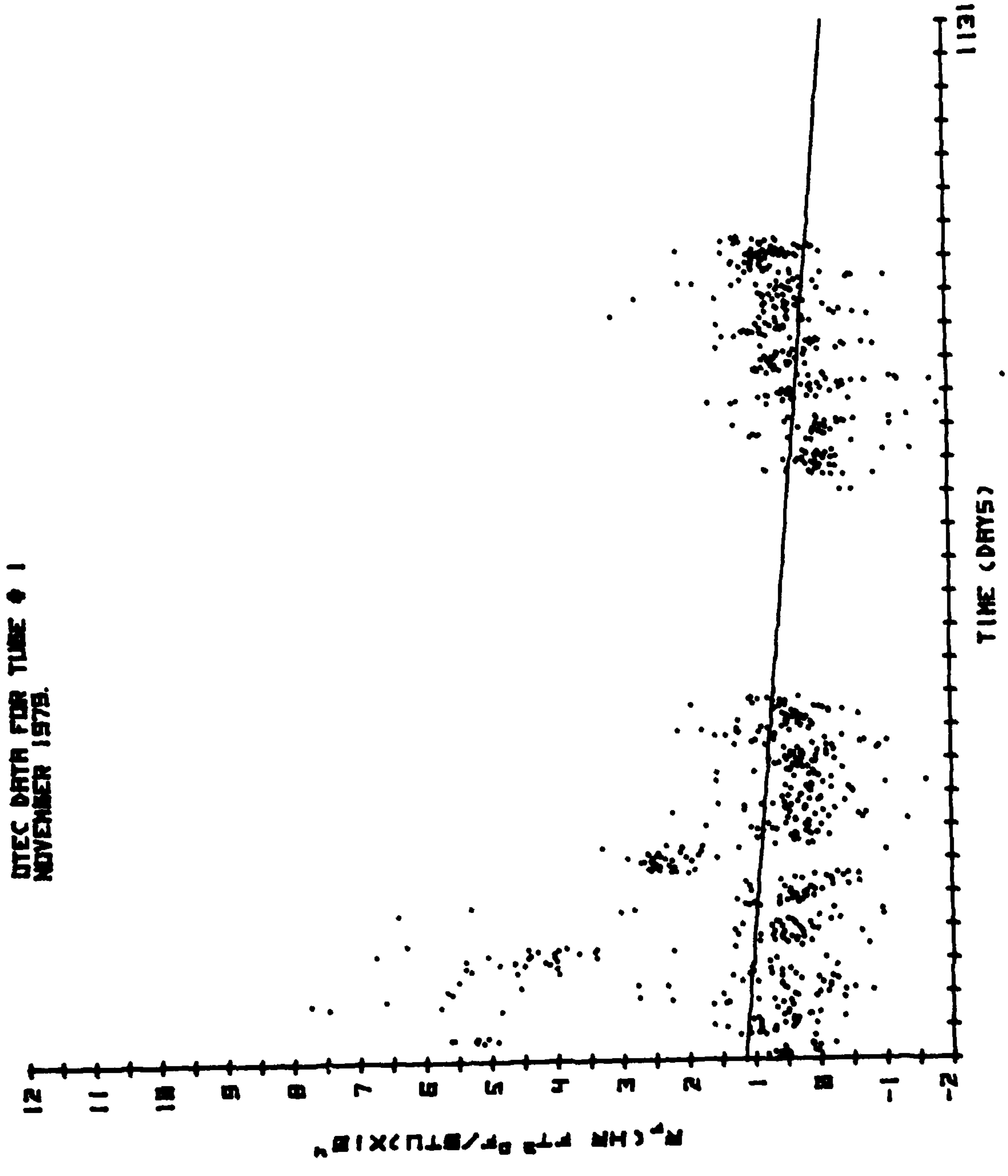

OTEC DATA FOR TUBE # 1
NOVEMBER 1979.
TIME (DAYS)
131
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE I-3.

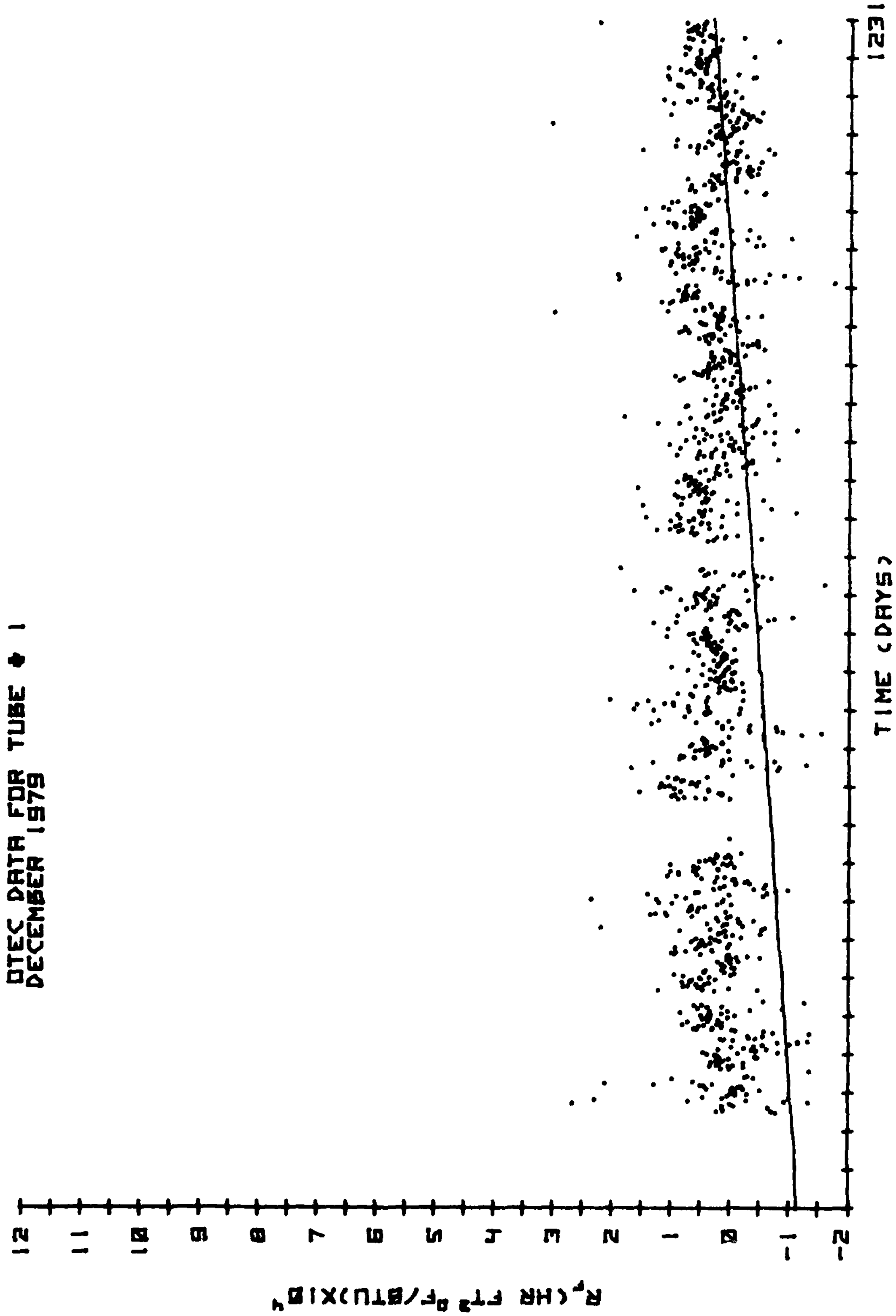

OTEC DATA FOR TUBE # 1
DECEMBER 1979
TIME (DAYS)
1231
R_f (HR FT2 °F/BTU)X10^4
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE I-4.

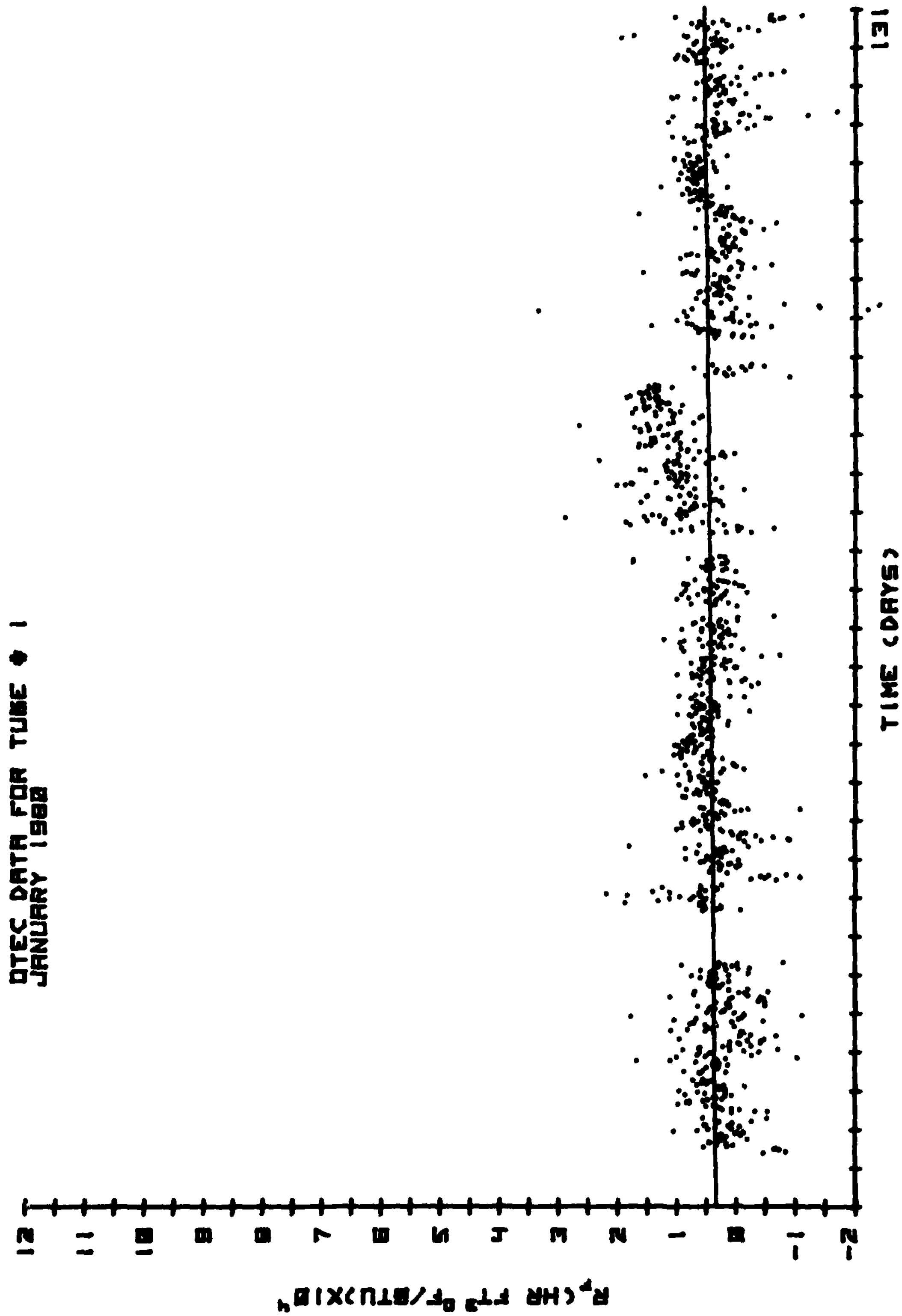

OTEC DATA FOR TUBE # 1
JANUARY 1980
TIME (DAYS)
31
R_f (HR FT² °F/BTU)X10⁴
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE I-5.

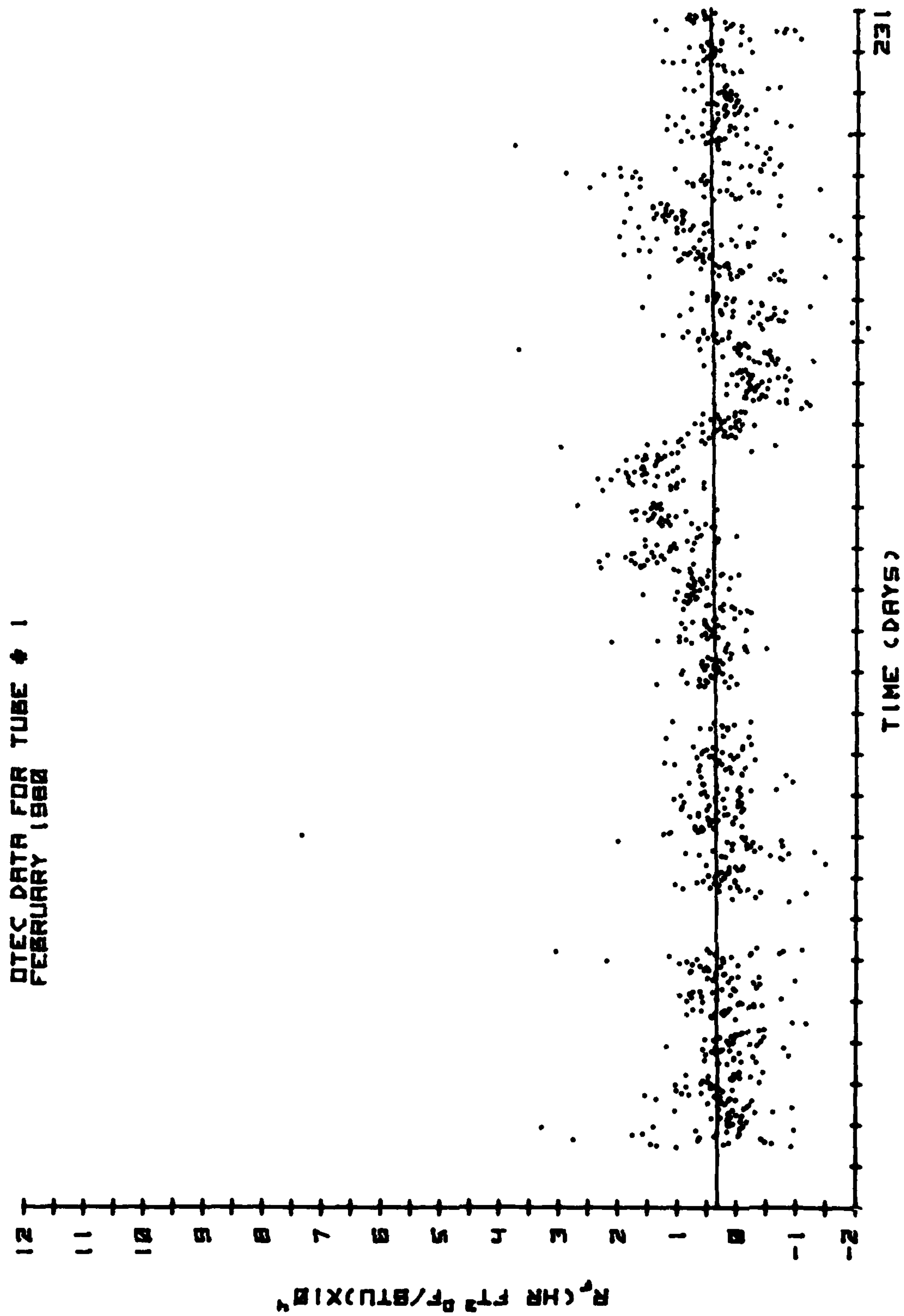

OTEC DATA FOR TUBE # 1
FEBRUARY 1980
TIME (DAYS)
231
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
R_f (HR FT^2 °F/BTU)X10^4

FIGURE I-6.

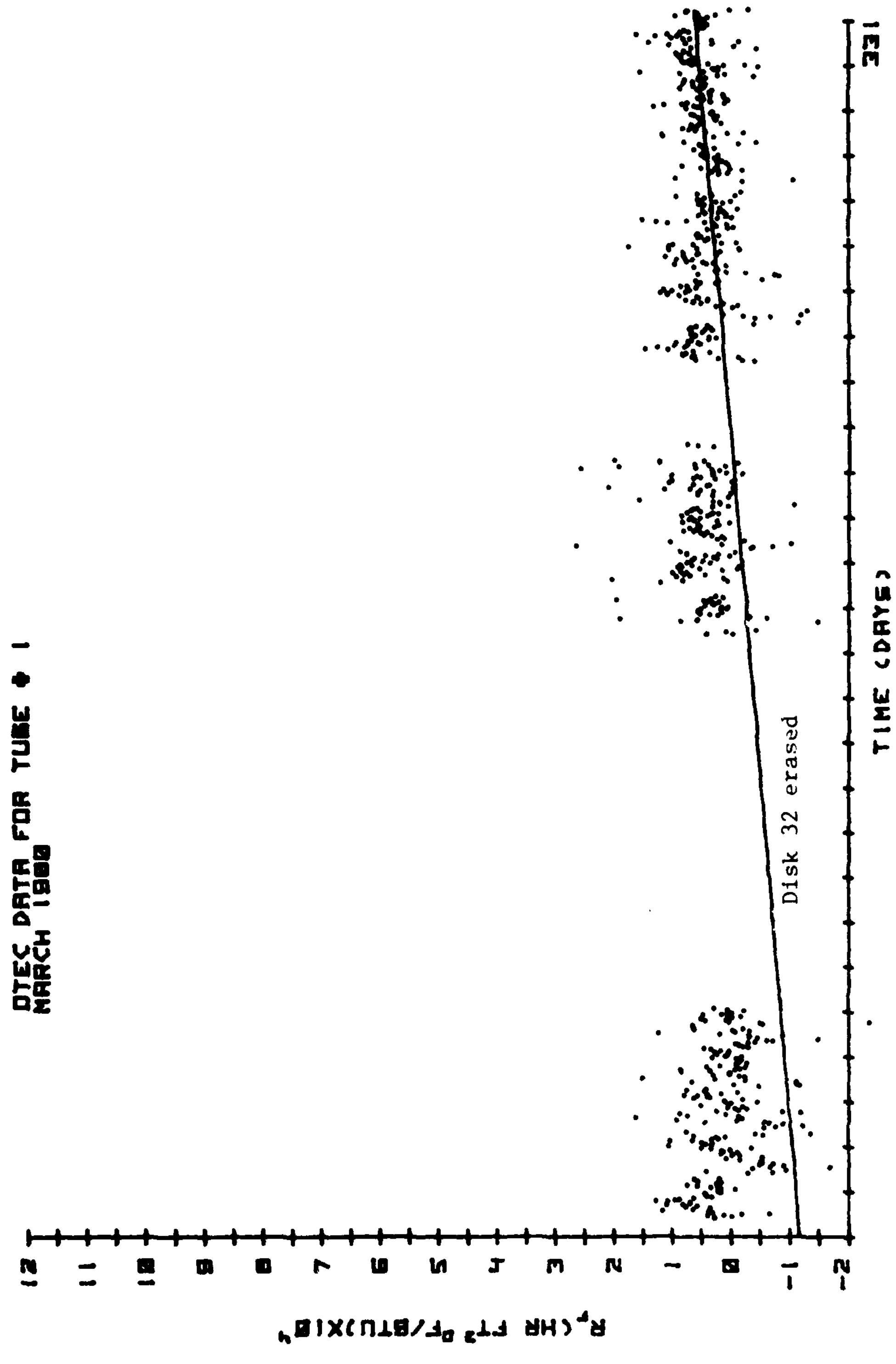

OTEC DATA FOR TUBE # 1
MARCH 1980
Disk 32 erased
TIME (DAYS)
331
R_f (HR FT² °F/BTU)X10⁴
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE I-7.

APPENDIX J

MONTHLY PLOTS OF Rf OBTAINED IN THE TITANIUM CONTROL, CLEANED DAILY

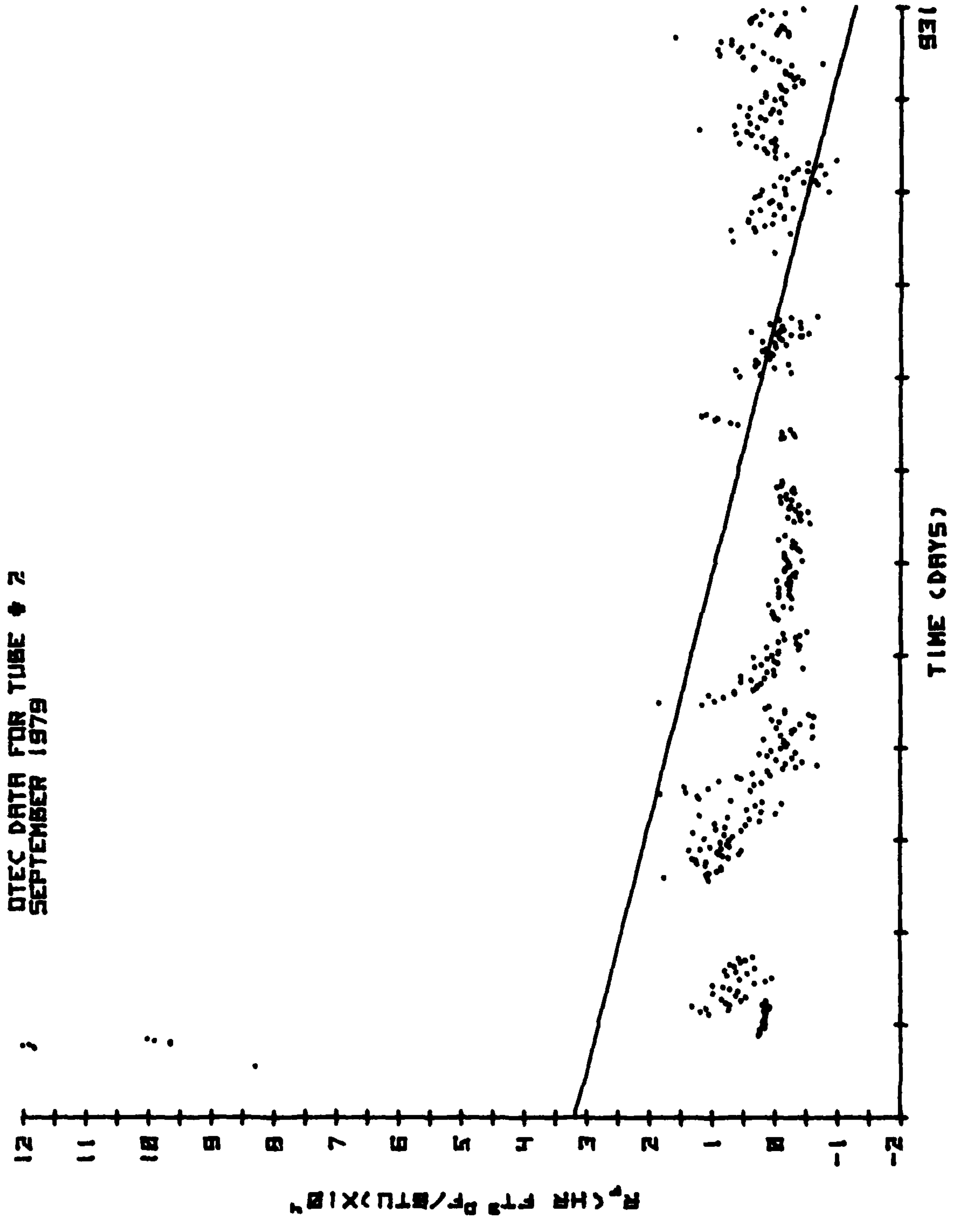

OTEC DATA FOR TUBE # 2
SEPTEMBER 1979
TIME (DAYS)
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
150

FIGURE J-1.

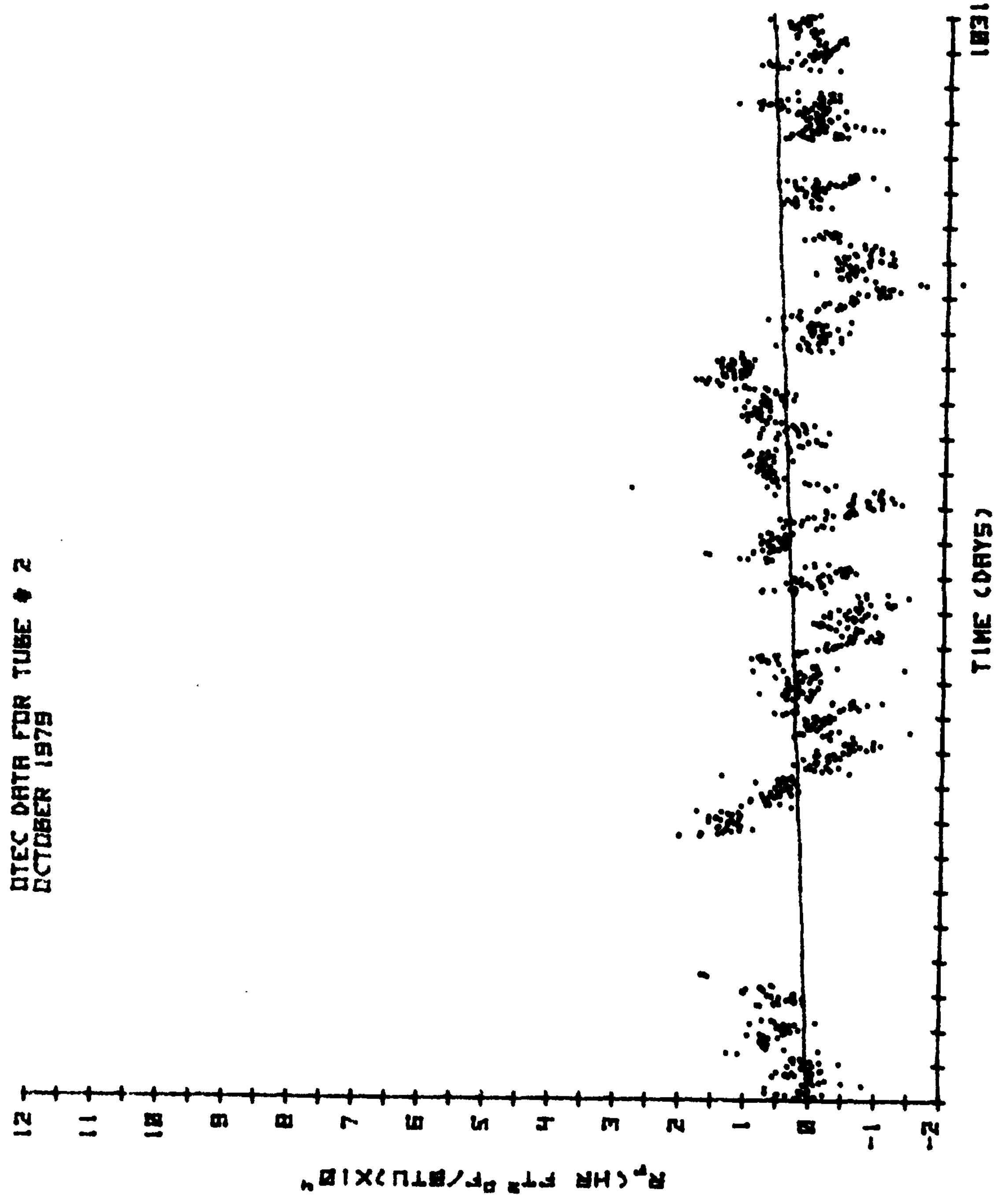

OTEC DATA FOR TUBE # 2
OCTOBER 1979
TIME (DAYS)
R_f (HR FT² °F/BTU)X10⁴
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE J-2.

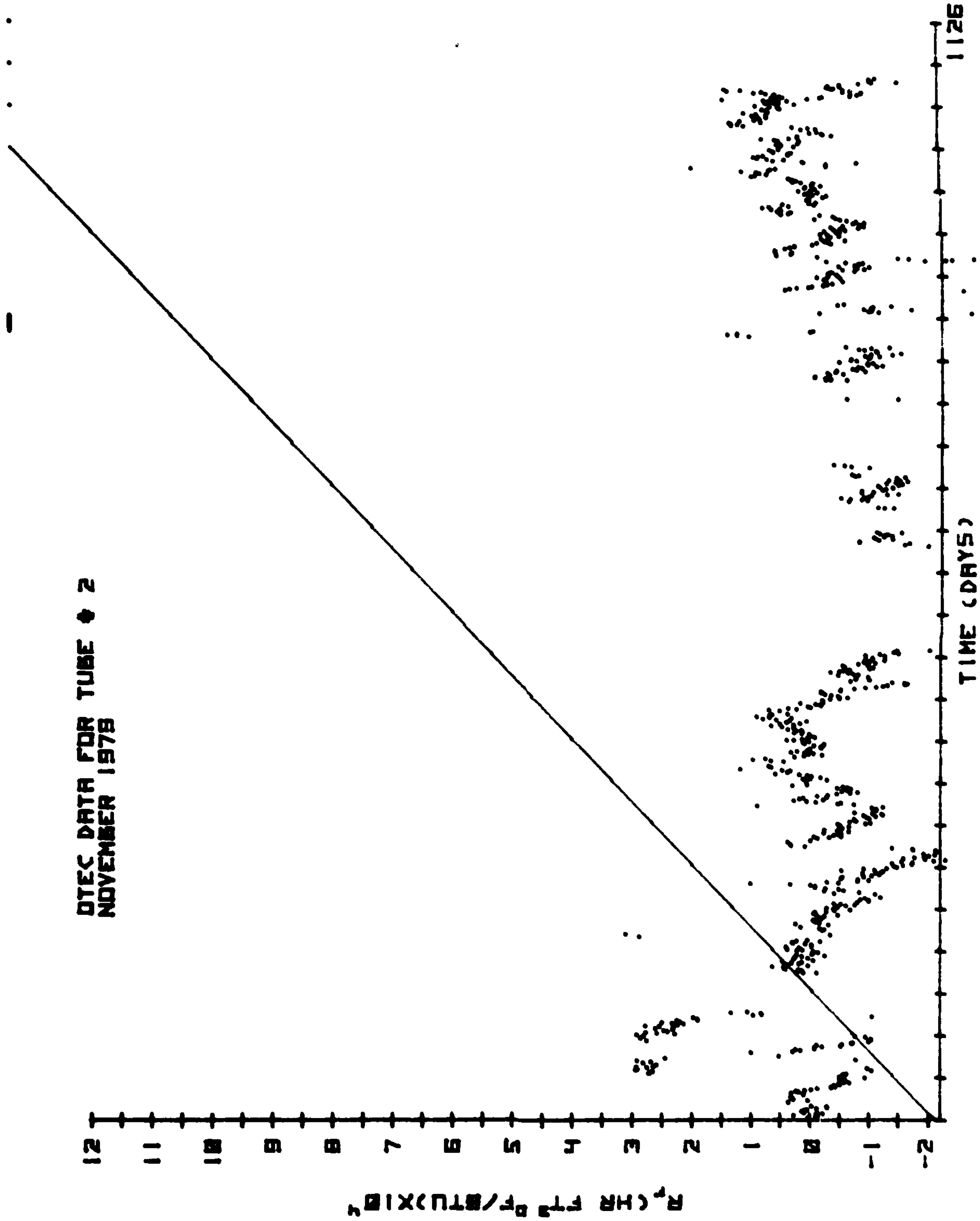

OTEC DATA FOR TUBE # 2
NOVEMBER 1979
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
R_f (HR FT² °F/BTU)×10⁴
TIME (DAYS)
1126

FIGURE J-3.

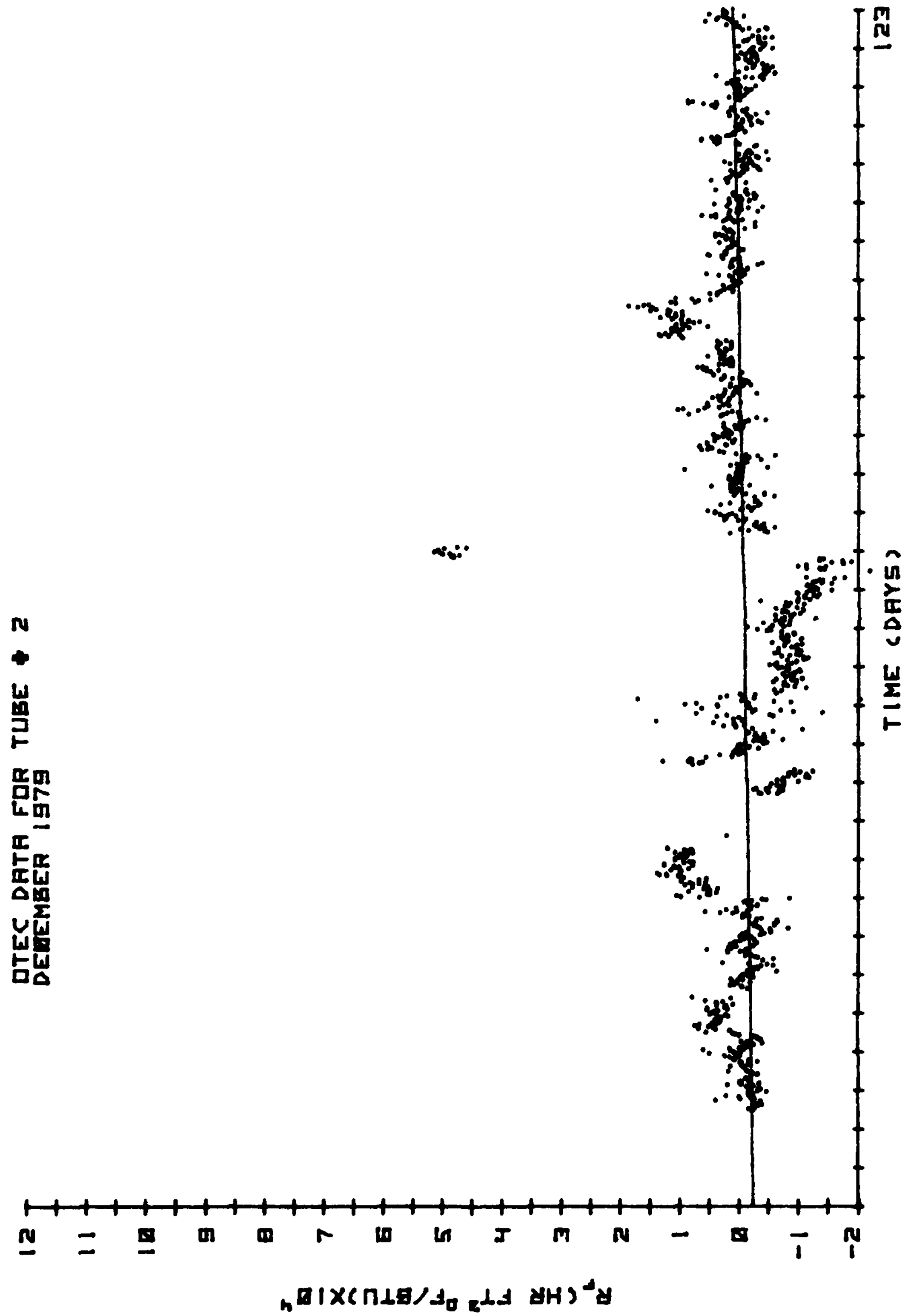

OTEC DATA FOR TUBE # 2
DECEMBER 1979
TIME (DAYS)
1231
R_f (HR FT² °F/BTU)X10⁴
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE J-4.

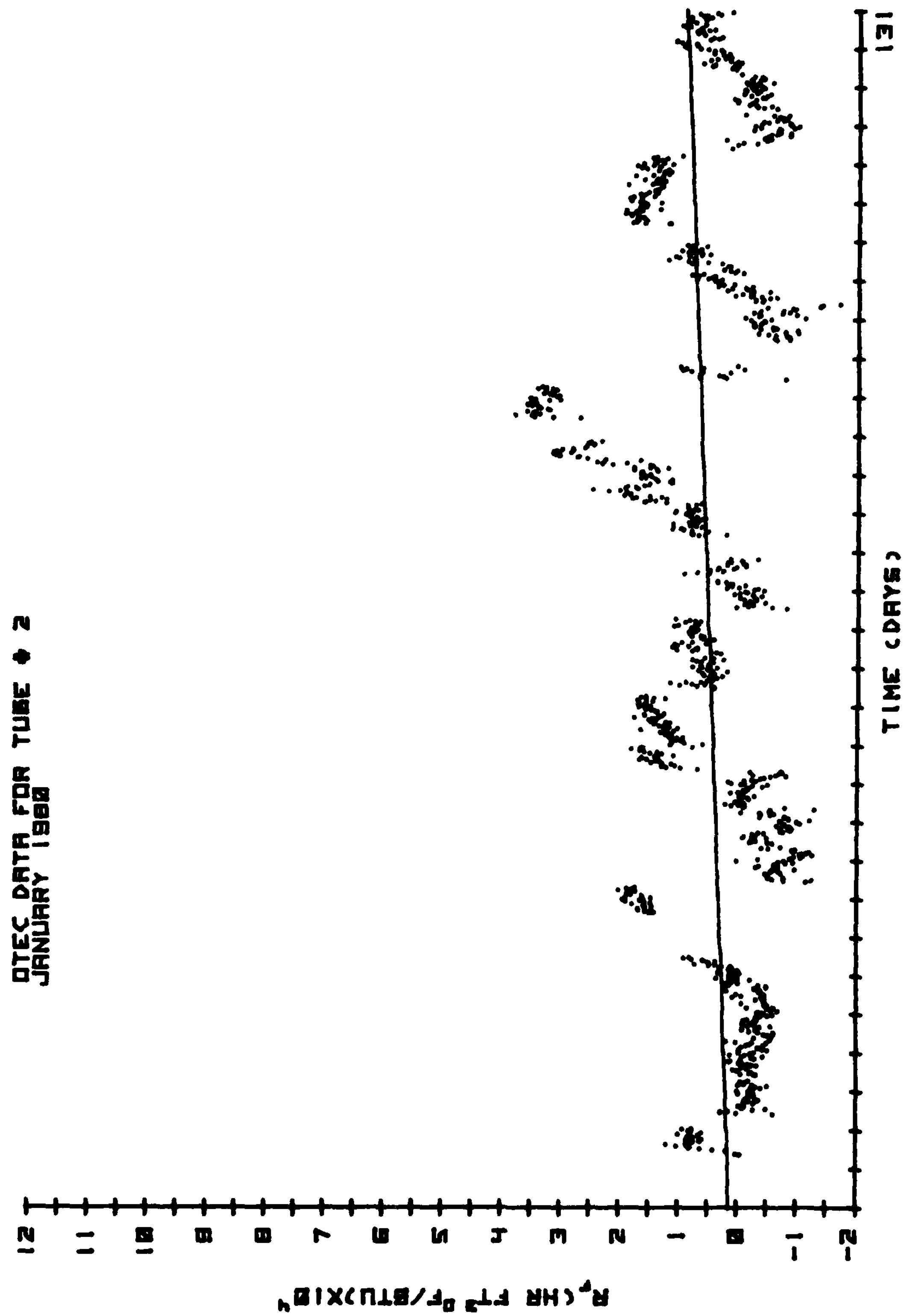

OTEC DATA FOR TUBE # 2
JANUARY 1980
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
R_f (HR FT² °F/BTU)X10⁴
TIME (DAYS)
131

FIGURE J-5.

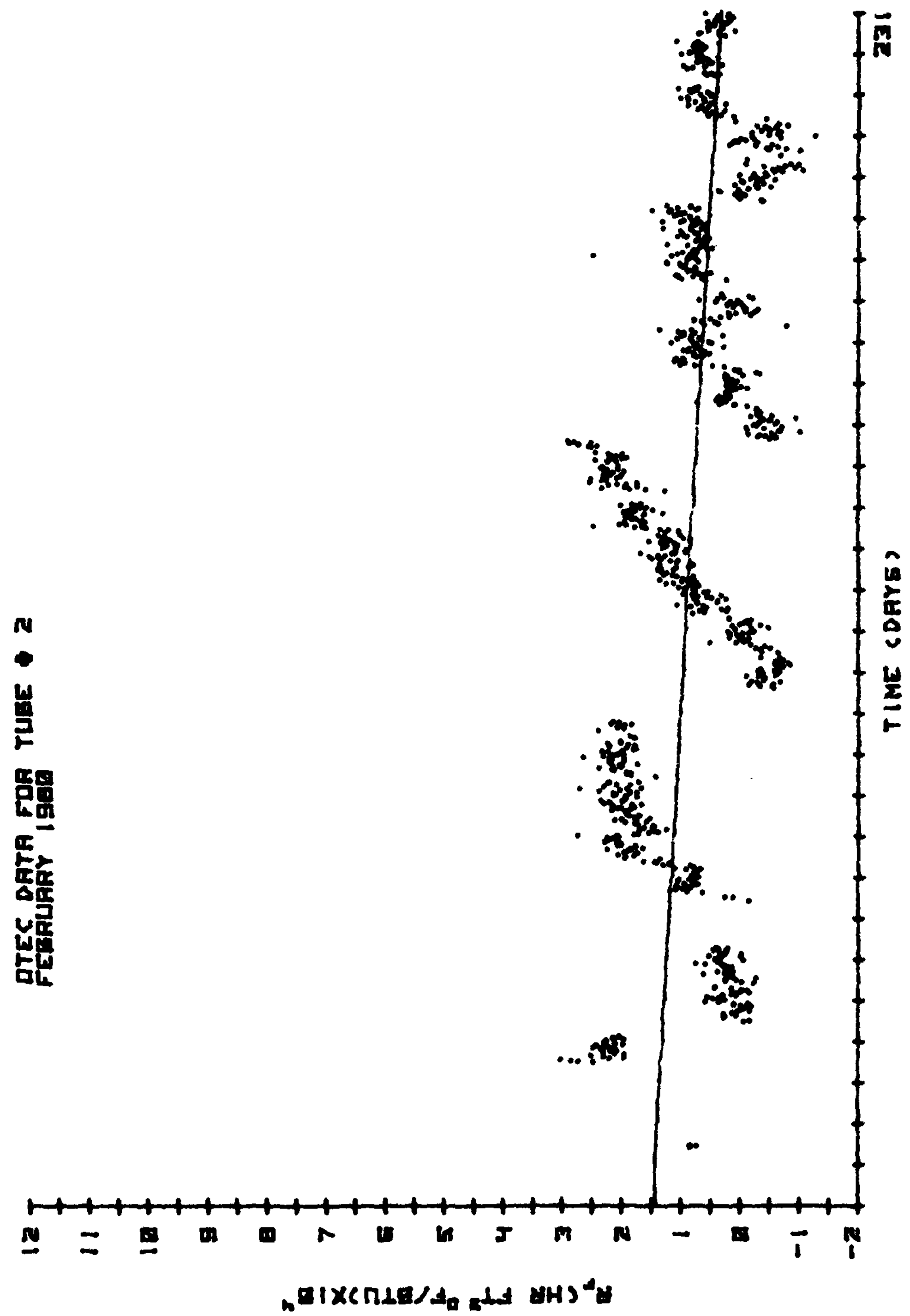

OTEC DATA FOR TUBE # 2
FEBRUARY 1980
TIME (DAYS)
231
R_f (HR FT² °F/BTU)X10⁴
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE J-6.

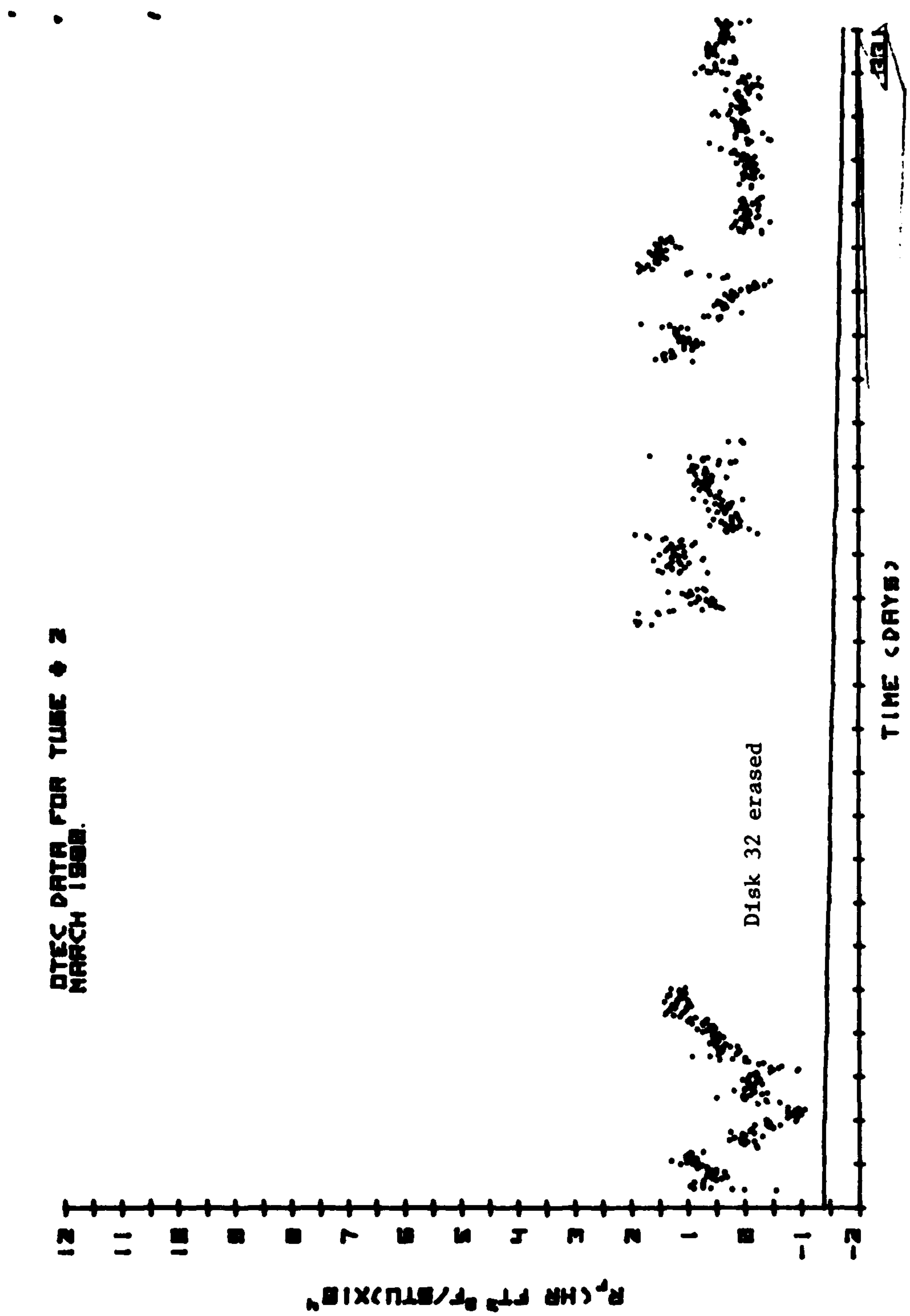

DTEC DATA FOR TUBE # 2
MARCH 1980
Disk 32 erased
TIME (DAYS)
R_f (HR FT² °F/BTU)X10⁴
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE J-7.

APPENDIX K

MONTHLY PLOTS OF Rf OBTAINED IN THE ALUMINUM FREELY FOULING CONTROL

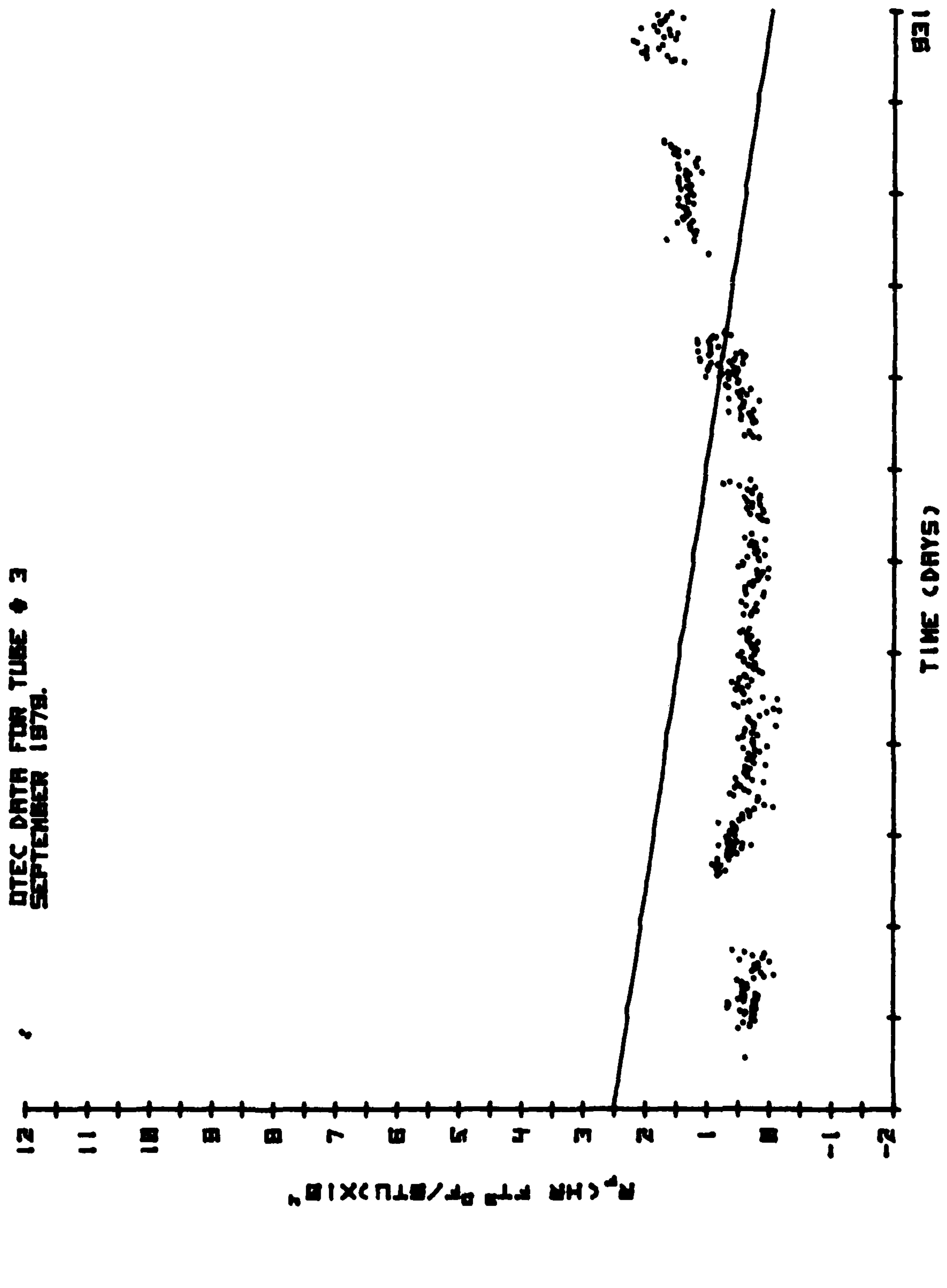


FIGURE K-1.

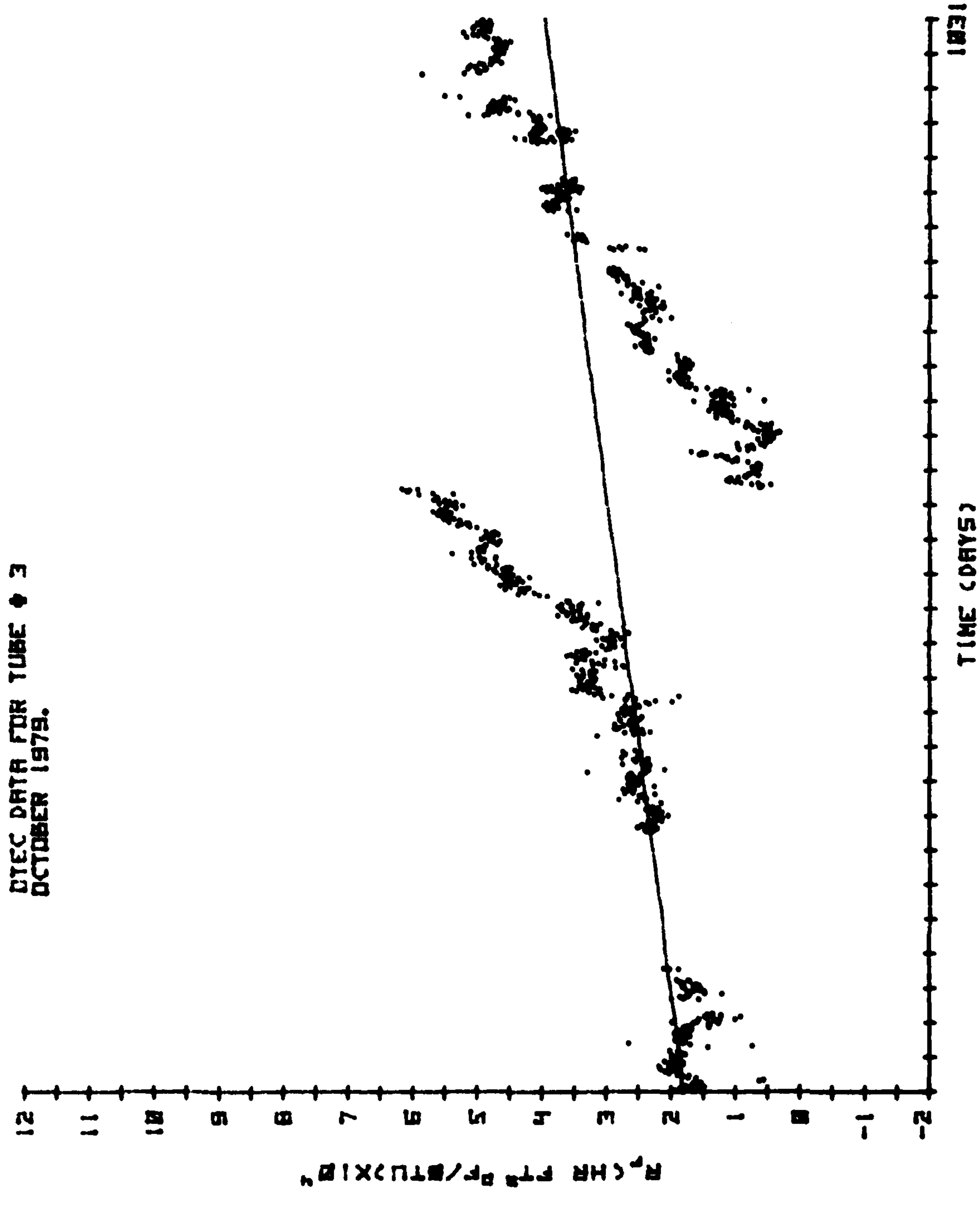

DTEC DATA FOR TUBE # 3
OCTOBER 1979.
TIME (DAYS)
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE K-2.

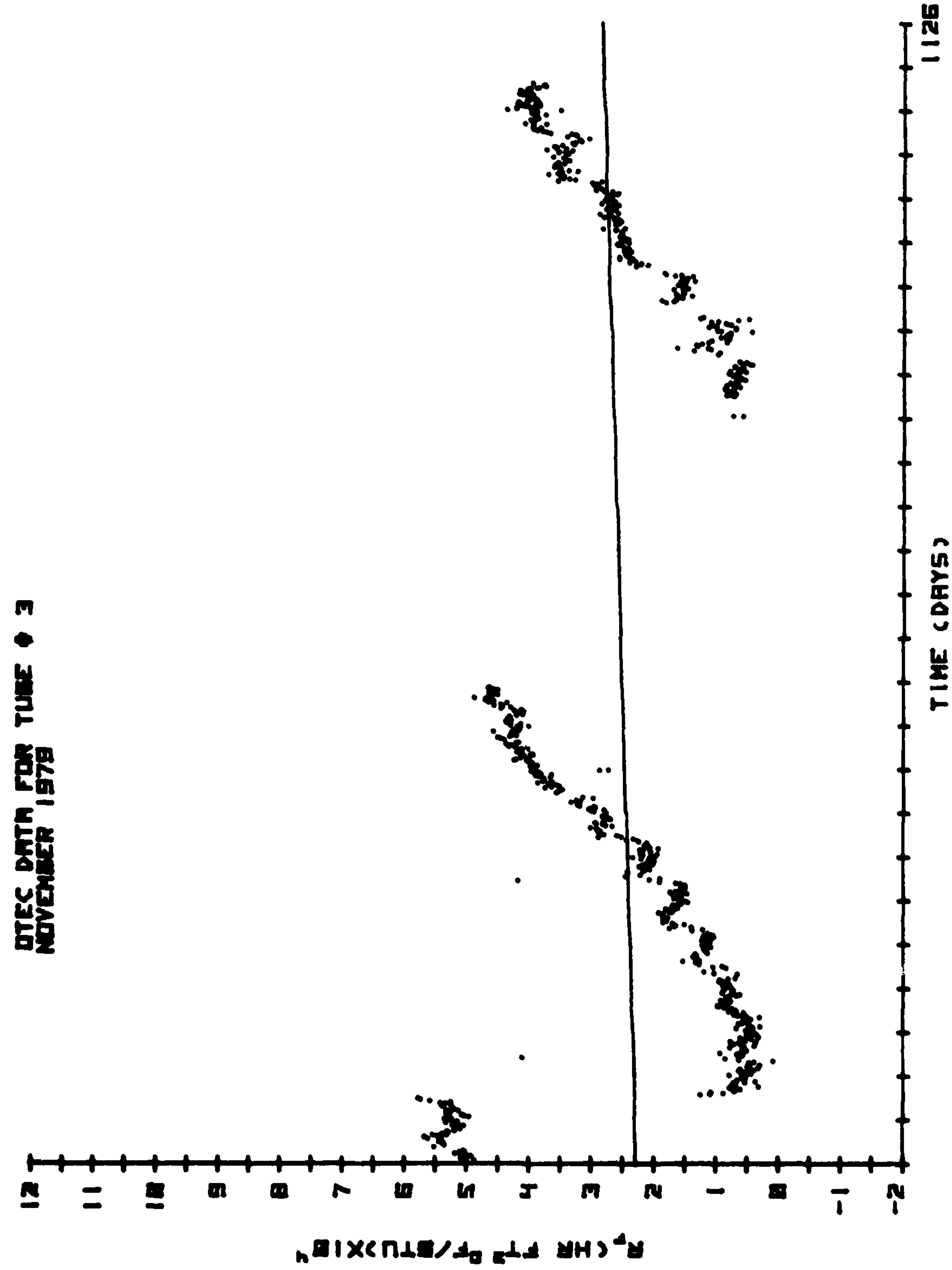

OTEC DATA FOR TUBE # 3
NOVEMBER 1979
TIME (DAYS)
1126
R (HR FT² °F/BTU)X10⁴
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE K-3.

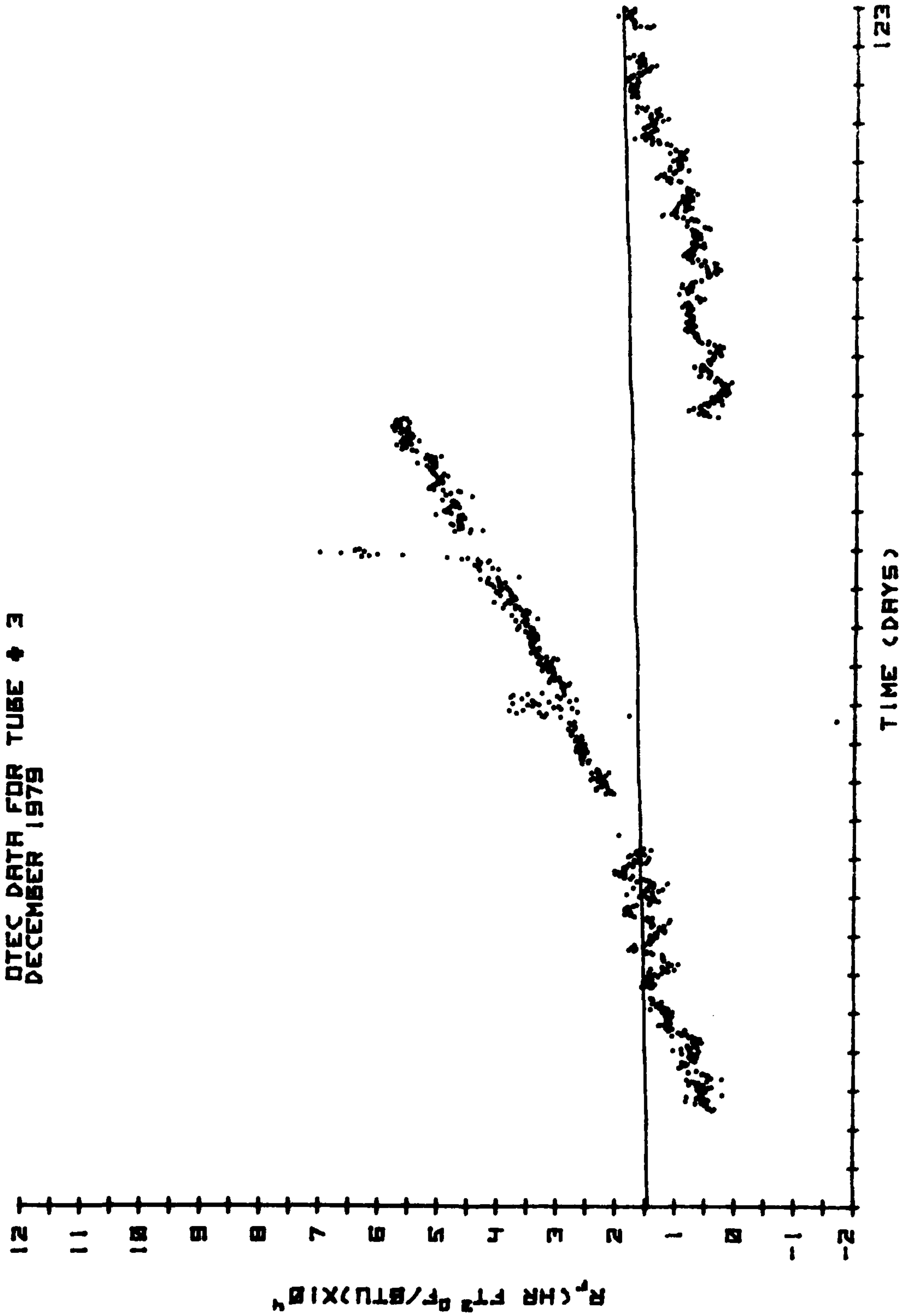

OTEC DATA FOR TUBE # 3
DECEMBER 1979
TIME (DAYS)
123
R_f (HR FT² °F/BTU)X10⁴
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE K-4.

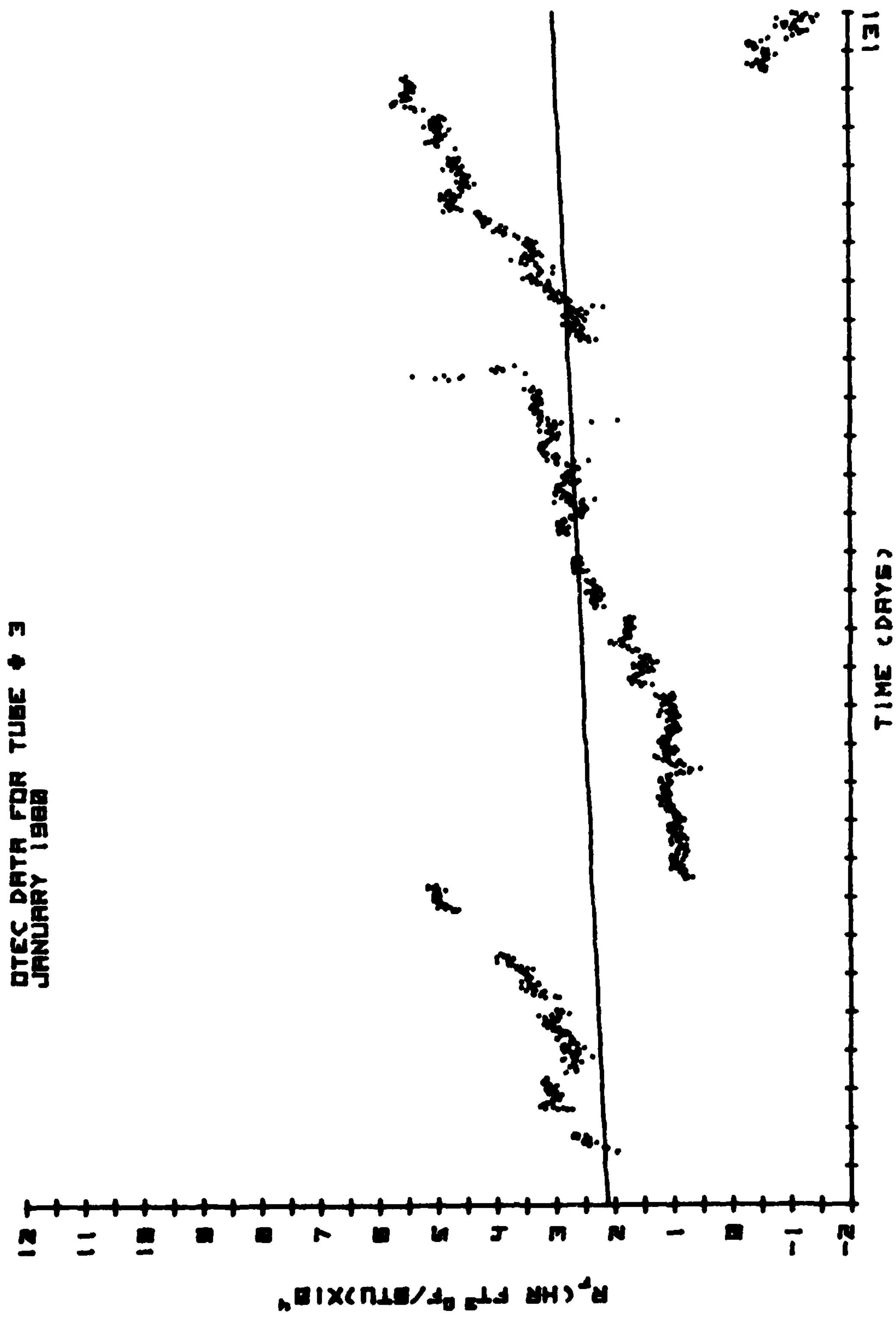

OTEC DATA FOR TUBE # 3
JANUARY 1980
TIME (DAYS)
131
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
R_f (HR FT² °F/BTU)X10⁴

FIGURE K-5.

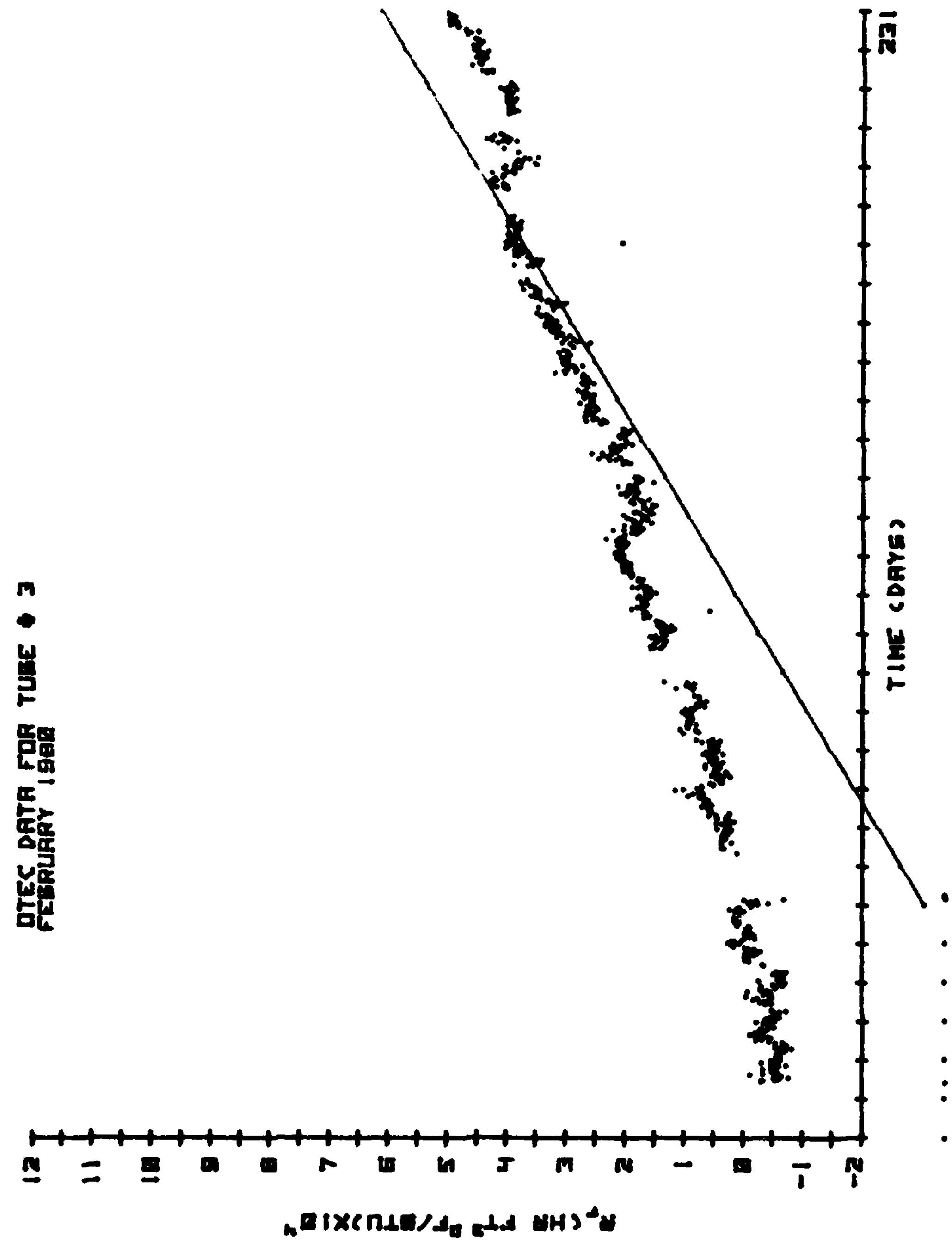


FIGURE K-6.

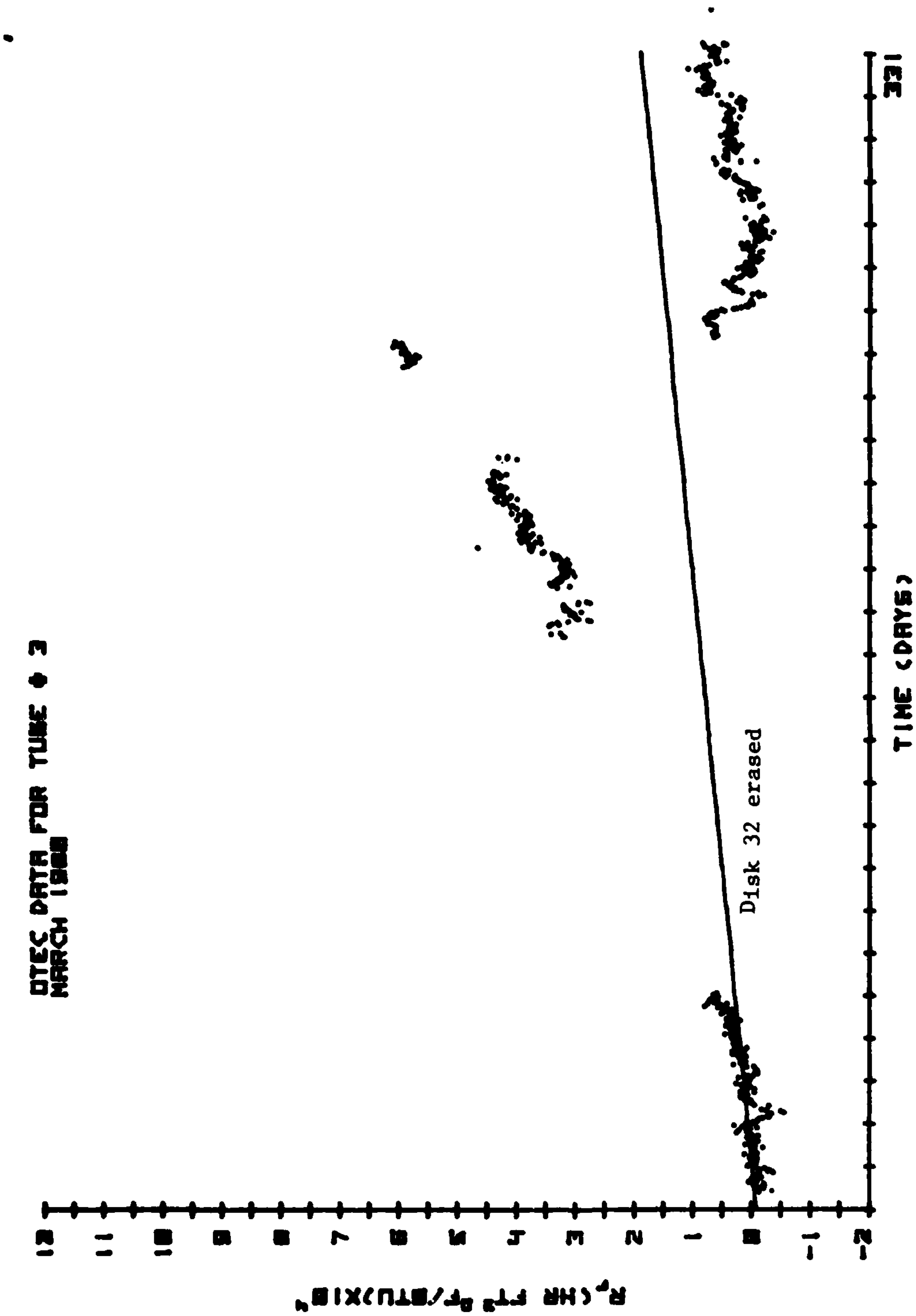

OTEC DATA FOR TUBE # 3
MARCH 1980
Disk 32 erased
TIME (DAYS)
331
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE K-7.

APPENDIX L

MONTHLY PLOTS OF THE Rf OBTAINED IN THE TITANIUM FREELY FOULING CONTROL

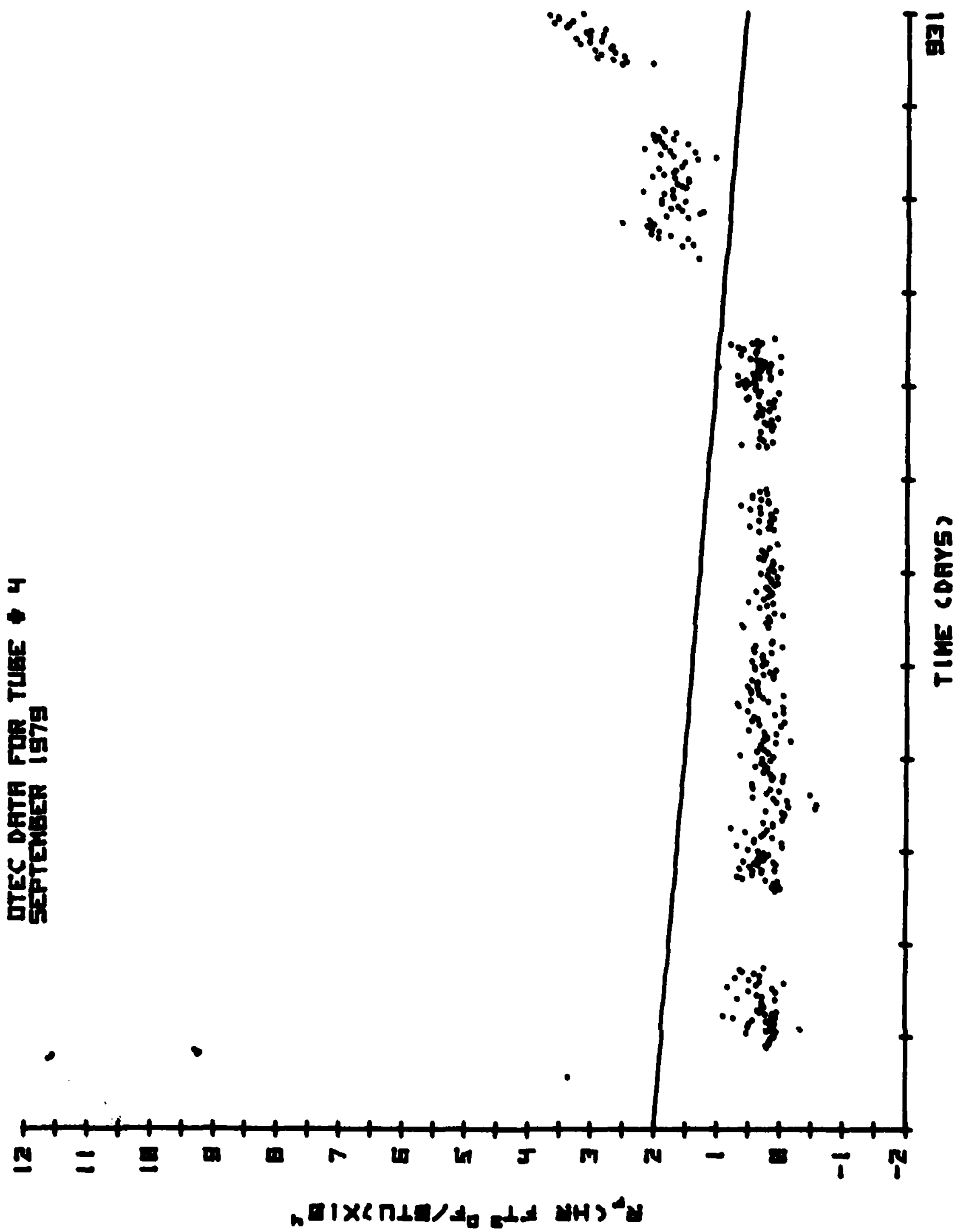

OTEC DATA FOR TUBE # 4
SEPTEMBER 1979
TIME (DAYS)
136
R_f (HR FT^2 °F/BTU)X10^4
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE L-1.

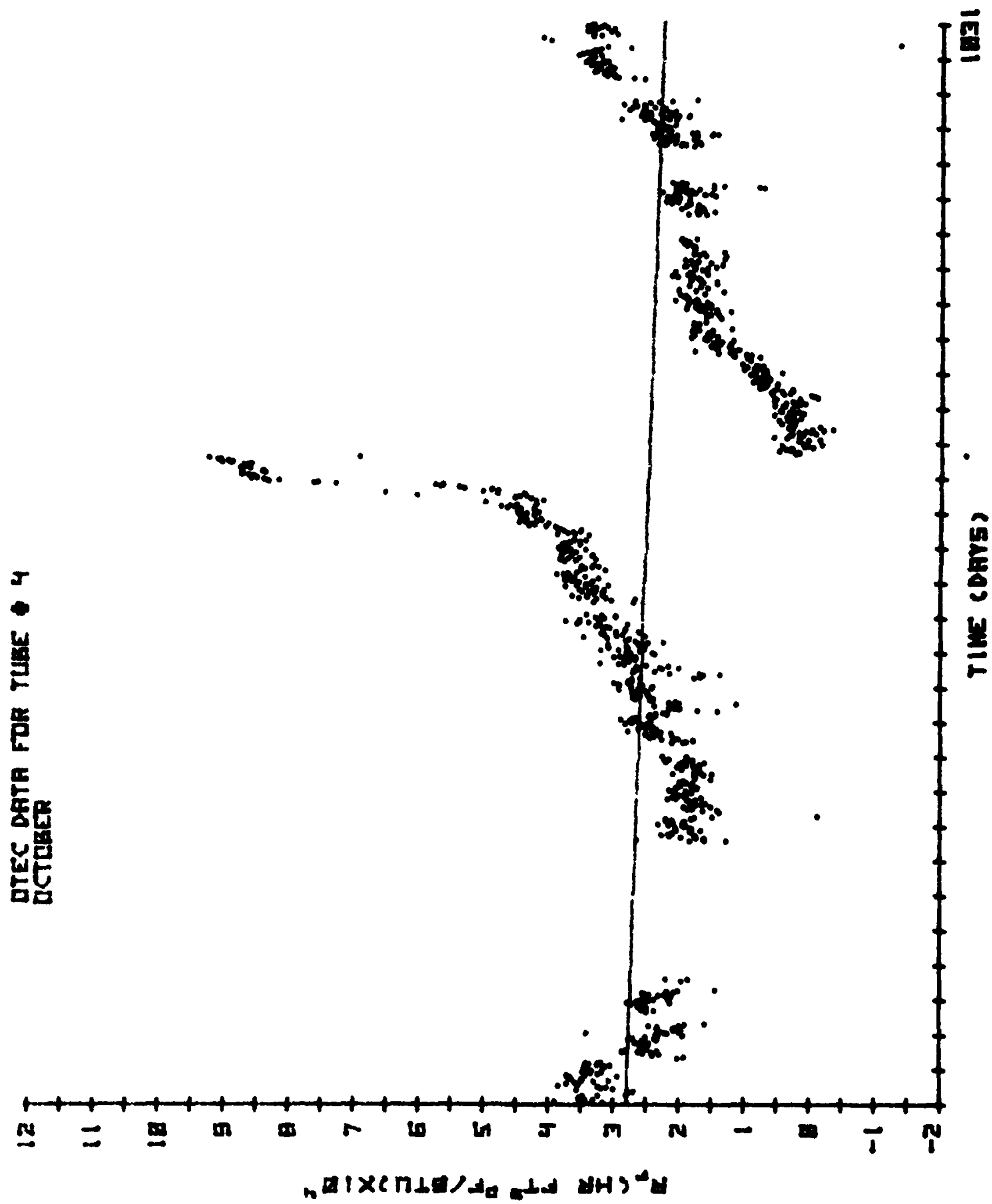


FIGURE L-2.

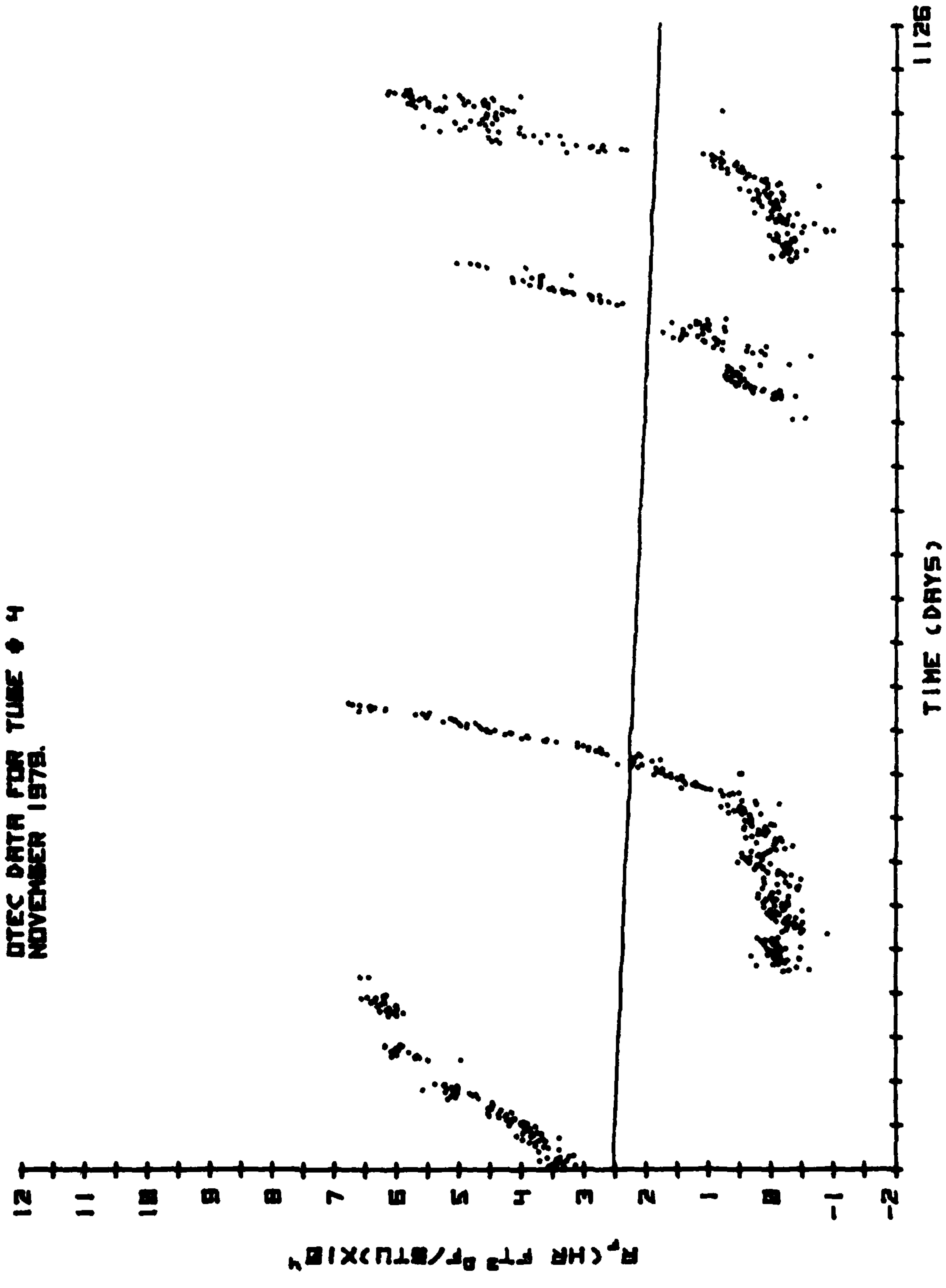

OTEC DATA FOR TUBE # 4
NOVEMBER 1979.
1126
TIME (DAYS)
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
R_f (HR FT² °F/BTU)X10⁴

FIGURE L-3.

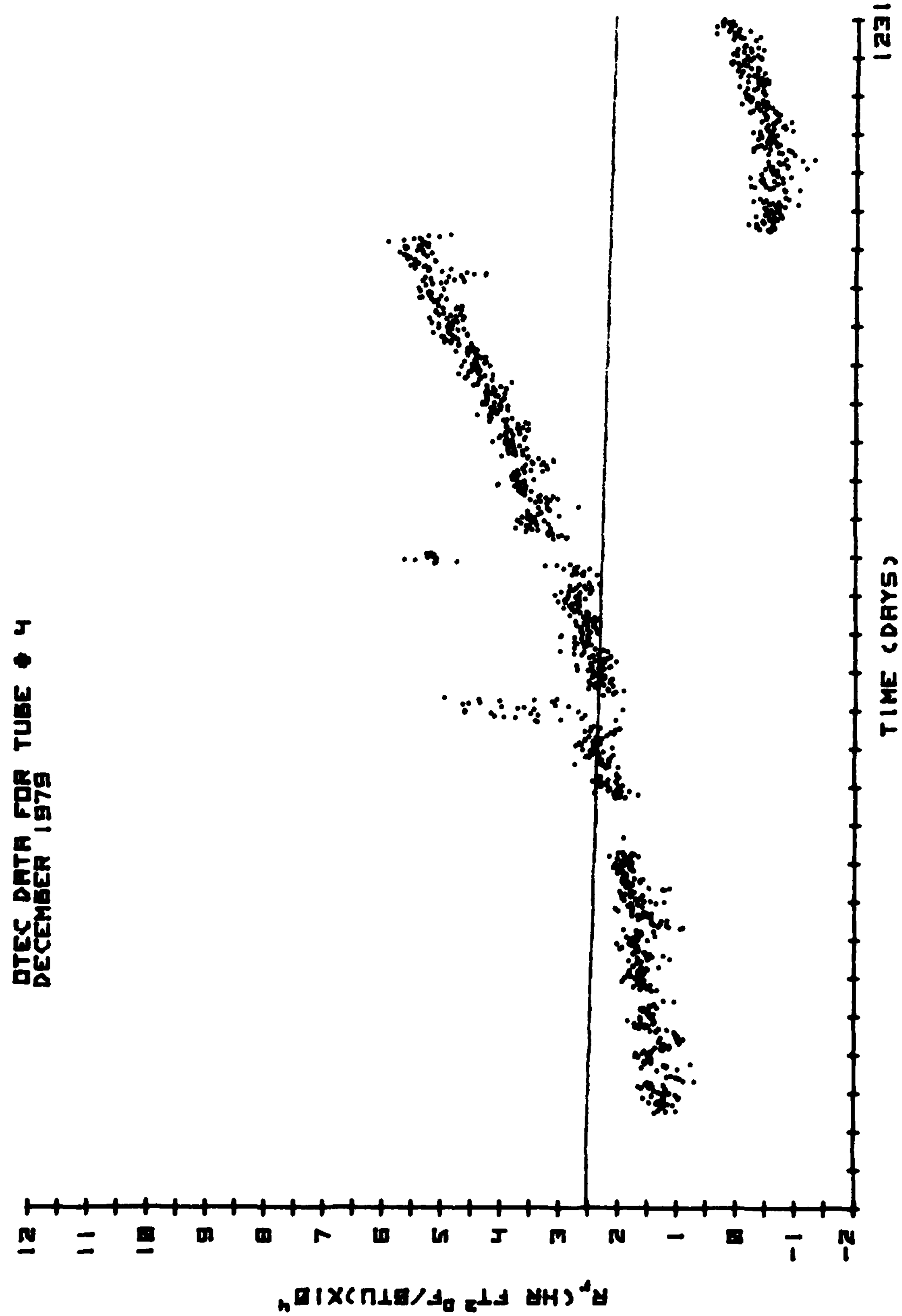

OTEC DATA FOR TUBE # 4
DECEMBER 1979
TIME (DAYS)
12 11 10 9 8 7 6 5 4 3 2 1 0 -1 -2

FIGURE L-4.

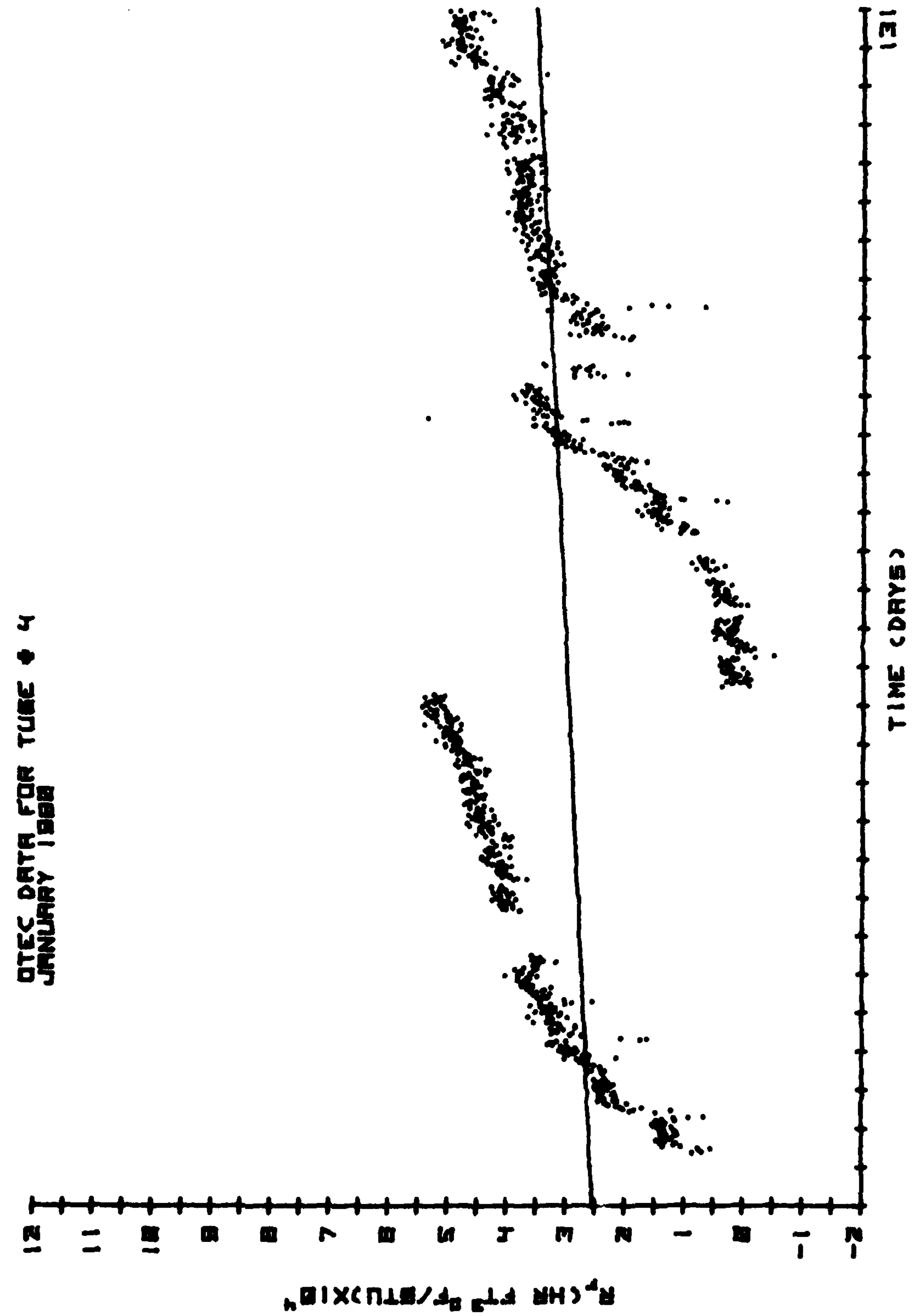


FIGURE L-5.

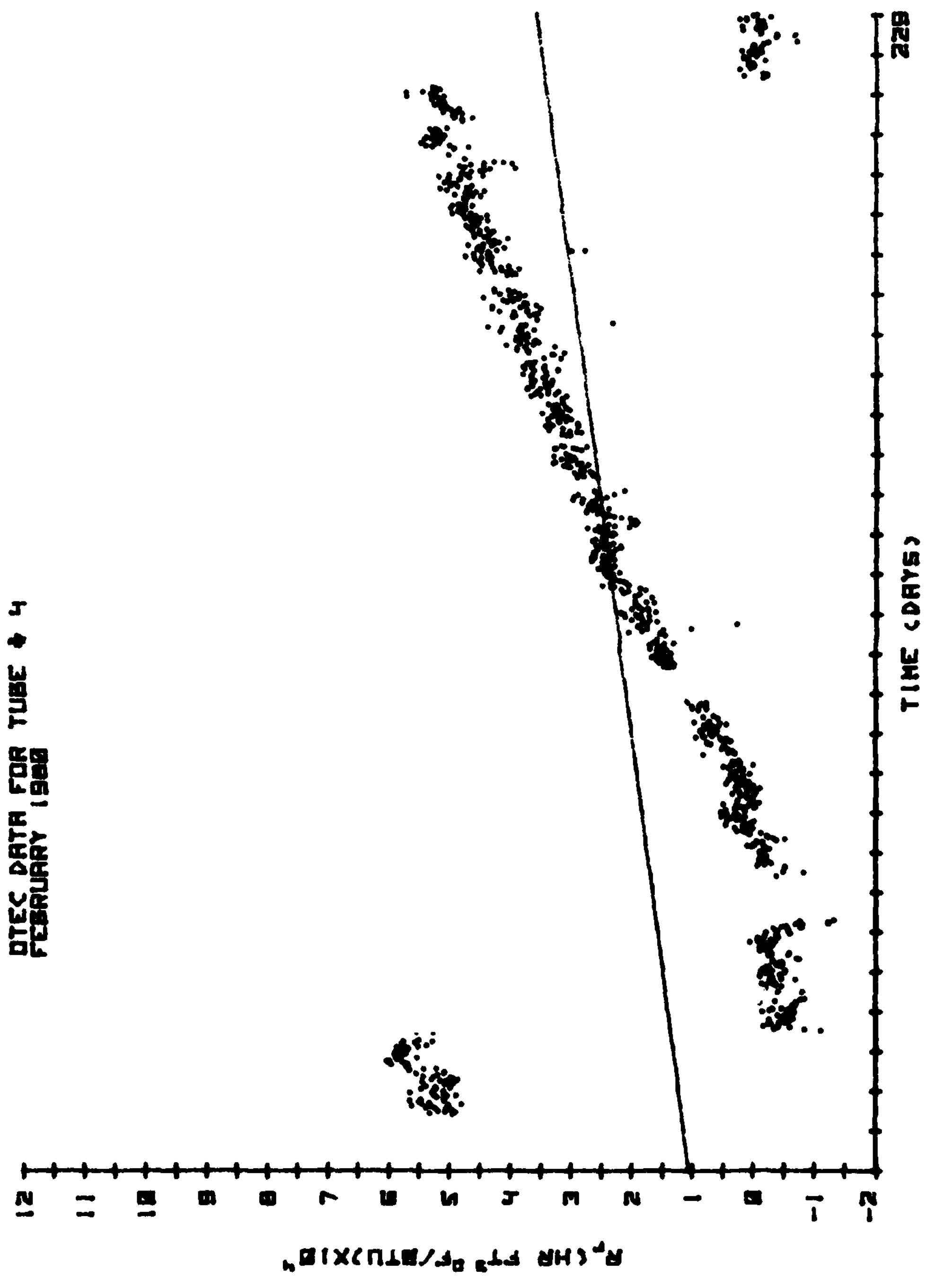

OTEC DATA FOR TUBE # 4
FEBRUARY 1980
TIME (DAYS)
228
R_f (HR FT^2 °F/BTU)X10^4
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE L-6.

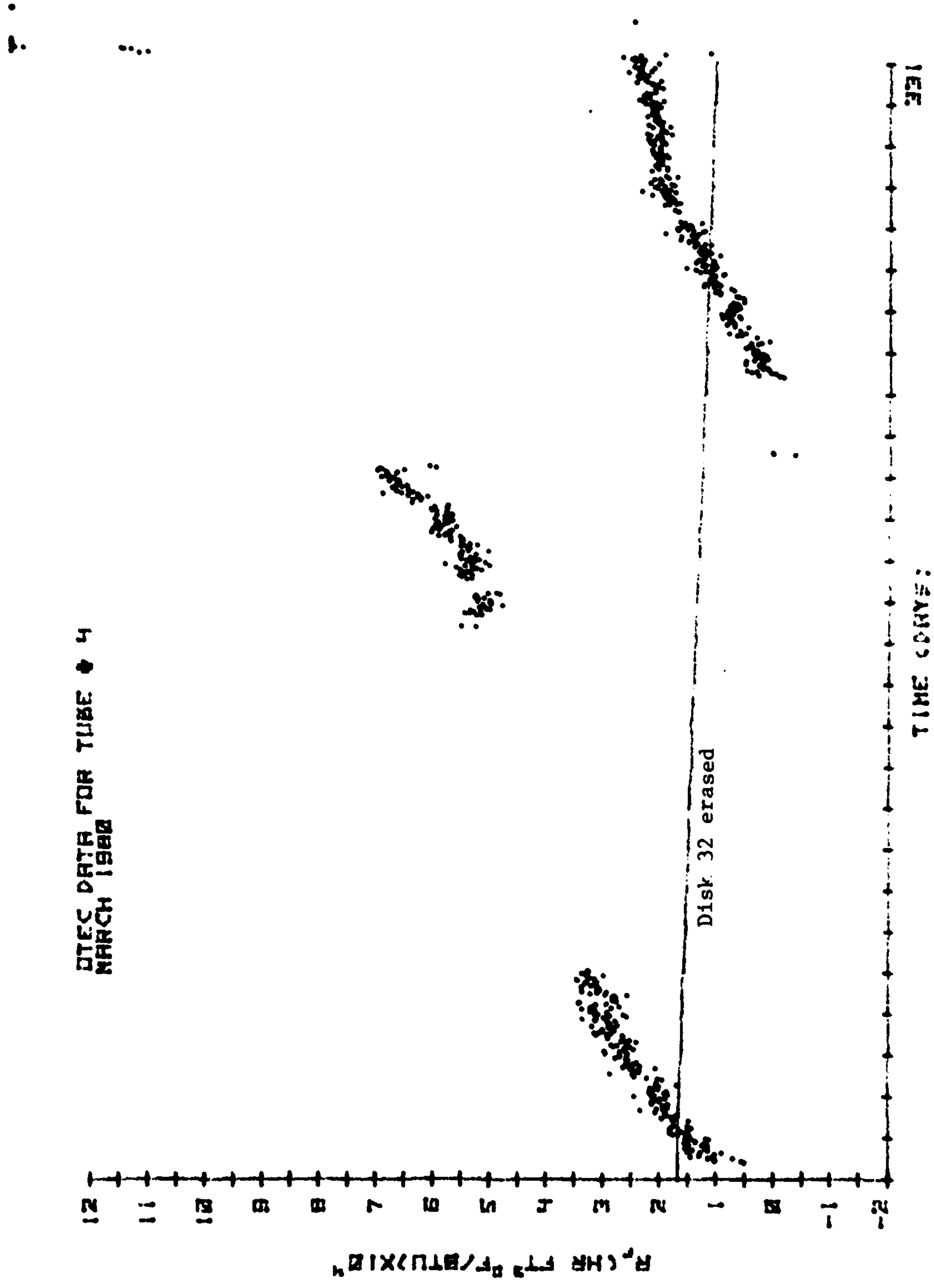

OTEC DATA FOR TUBE # 4
MARCH 1980
Disk 32 erased
TIME CURVE
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2

FIGURE L-7.

DATE
ILMED
-8